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OXIDATION AT CHUQUICAMATA, CHILE.

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ABSTRACT.

Experimental work done by the Geophysical Laboratory investigators and others on the stability relations of oxidized minerals of copper and iron is first summarized because of its bearing upon the processes of oxidation at Chuquicamata. Following is a description of the general geological features at Chuquicamata which have influenced oxidation, including the climate and physiography of the region, the rock elements involved, and the nature of the primary mineralization and rock alteration.

The discordance between the top of the sulphide zone and the present water table is explained by recent changes in the position of the water table. Several analyses of the groundwater are presented as a guide to the composition of the waters that caused the oxidation.

Oxidation of different types of sulphide ore and secondary changes taking place in the zone of oxidation can be observed in the open pit and in churn drill cuttings. These are described and explained in the light of the conclusions reached from experimental work.

With experience gained from observation and deduction, hypotheses are advanced to account for the origin of the main oxidized orebody, the waste zone which locally overlies the sulphide zone, and the zone of partial oxidation which over much of the mine separates the sulphide and oxidized orebodies.

Finally, the behavior of some of the less abundant elements during oxidation is described.

INTRODUCTION.

THE chemical processes that control oxidation of copper deposits in humid and semi-arid climates have been well recognized and described in the literature. Experimental work at the Geophysical Laboratory, Washington, D. C., has made possible approximate predictions as to the mineralogy and paragenesis of oxidized copper ores situated in extremely arid climates. The copper deposit at Chuquicamata, Chile, strikingly confirms the experimental work, and coupled with the fact that it is the largest known copper deposit in the world, makes it of particular interest to mining geologists.

The writer was employed as mine geologist for the Chile Exploration Company from 1935–38. The substance of this paper was first submitted as a private report to the Company in May 1938. Contemporaneous with the writer's stay in Chile, M. C.

Bandy, who had formerly been on the staff of the Chile Exploration Company, was also studying independently at Harvard University the mineralogy and paragenesis of the Chuquicamata ores and those of two nearby deposits, Quetena and Alcaparossa. The results of his work were published in 1938.[1] Bandy discusses in considerable detail the rare minerals and their paragenesis as noted principally from hand specimens; in contrast, this paper attempts to present the significant field relations and to emphasize only those minerals that are quantitatively important in the various types of ore.

In a district studied by many geologists, a large body of facts and opinions is bound to accumulate over the years. A geologist new in the district tends to absorb these and perhaps to adopt unconsciously many as his own. Geologists who had worked at Chuquicamata prior to 1935, and to whom the writer is indebted in this manner, include W. Lindgren, E. S. Bastin, Reno Sales, A. V. Taylor, Jr., V. M. Lopez, and M. C. Bandy. W. S. March, Jr., and A. E. Weissenborn, respectively Chief Geologist and former Assistant Chief Geologist for the Company, have contributed to the value of many of the ideas here presented through their mapping, discussion, and friendly criticism. The mapping of W. S. Bronkie, David Samuels, and Lester Zeihen, other geologists on the mine staff in recent years, has helped further in the establishment of the facts of the field occurrence. Professors Russell Gibson and Harry Berman of Harvard University, and Dr. George F. Seager have aided by criticizing the paper. The writer is especially grateful to the Chile Exploration Company for permission to publish.

SUMMARY OF EXPERIMENTAL WORK ON THE STABILITY OF OXIDIZED MINERALS OF COPPER AND IRON.

To clarify the description of the oxidation at Chuquicamata, a summary is presented first of some of the conclusions that may be

[1] Bandy, M. C.: Mineralogy of three sulphate deposits of northern Chile. Amer. Min. 23: 669–760, 1938.

deduced from the work of the Geophysical Laboratory [2] and of Locke and his associates [3] on the stability relations of some of the oxidized minerals of copper and iron. Compositions of the minerals mentioned in this paper, because of the rarity of many, are given in Table 1.

(1) In the three component system, $CuO–SO_3–H_2O$, at 50° C., as shown in Fig. 1, chalcanthite forms from solutions of high SO_3

TABLE 1.

COMPOSITION OF THE NATURAL HYDROUS FERRIC SULPHATES.

Mineral	Formula	Composition in Weight Per Cent				Comments
		FeO	Fe_2O_3	SO_3	H_2O	
Romerite....	$FeO.Fe_2O_3.4SO_3.14H_2O$	9.9	22.1	33.2	34.8	Normal
Voltaite.....	$3(FeO.K_2O).Fe_2O_3.6SO_3.9H_2O$	21.2 (Part K_2O)	15.7 (Part Al_2O_3)	47.2	15.9	Normal
Rhomboclase	$Fe_2O_3.4SO_3.9H_2O$	—	24.9	49.9	25.2	Acid
Kornelite....	$Fe_2O_3.3SO_3.7H_2O$	—	30.4	45.8	23.8	Normal
Coquimbite..	$Fe_2O_3.3SO_3.9H_2O$	—	28.4	42.7	28.9	Normal
Copiapite....	$2Fe_2O_3.5SO_3.17H_2O$	—	31.2	28.9	29.9	Basic
Amarantite..	$Fe_2O_3.2SO_3.7H_2O$	—	35.9	35.9	28.2	Basic
Castanite....	$Fe_2O_3.2SO_3.8H_2O$	—	34.4	34.5	31.5	Basic
Fibroferrite..	$Fe_2O_3.2SO_3.10H_2O$	—	32.0	32.0	36.0	Basic
Jarosite.....	$K_2O.3Fe_2O_3.4SO_3.6H_2O$	K_2O 9.4	47.9	31.9	10.8	Basic

COMPOSITION OF SOME OF THE COPPER MINERALS AT CHUQUICAMATA.

Mineral	Formula	Composition				Comments
		CuO	SO_3	H_2O	Na_2O	
Cuprite.....	Cu_2O	—	—	—	—	—
Melaconite....	CuO	100.0	—	—	—	—
Brochantite....	$4CuO.SO_3.3H_2O$	70.3	17.7	12.0	—	Basic
Antlerite.....	$3CuO.SO_3.2H_2O$	67.2	22.5	10.3	—	Basic
Chalcanthite...	$CuO.SO_3.5H_2O$	31.8	32.1	36.1	—	Normal
Krohnkite.....	$CuO.Na_2O.2SO_3.2H_2O$	23.6	47.4	10.6	18.4	Normal
Natrochalcite..	$4CuO.Na_2O.3SO_3.3H_2O$	47.3	35.6	8.0	9.2	Basic
Cuprocopiapite	$CuO.2Fe_2O_3.6SO_3.15H_2O$	7.1	42.7	22.7	Fe_2O_3=27.5	Basic

[2] Posnjak, E. and Merwin, H. E.: The system $Fe_2O_3–SO_3–H_2O$. Jour. Amer. Chem. Soc. 44 (2): 1965–1994, 1922. Posnjak, E. and Tunell, G.: The system $CuO–SO_3–H_2O$. Amer. Jour. Sci., 5th ser. 18: 1–34, 1929. Tunell, G. and Posnjak, E.: A portion of the system, $F_2O_3–CuO–SO_3–H_2O$. Jour. Phys. Chem. 35: 929–946, 1931.

[3] Locke, A.: Leached Outcrops as Guides to Copper Ores. Baltimore, 1931.

TABLE 1.—(*continued*)

COMPOSITION OF OTHER MINERALS FROM CHUQUICAMATA THAT ARE MENTIONED IN THIS PAPER.

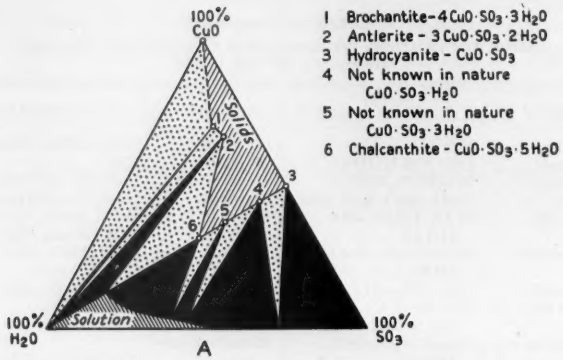
Mineral	Formula	Mineral	Formula
Anglesite	$PbSO_4$	Lindgrenite	$3CuO.2MoO_3.H_2O$
Atacamite	$CuO.CuCl_2.3H_2O$	Marshite	CuI
Bellingerite	$3Cu(IO_3)_2.2H_2O$	Metavoltine	Formula uncertain
Blodite	$Na_2O.MgO.2SO_3.4H_2O$	Mirabilite	$Na_2O.SO_3.10H_2O$
Botryogen	$Fe_2O_3.2MgO.4SO_3.14H_2O$	Molybdic Ochre	$Fe_2O_3.MoO_3.7\frac{1}{2}H_2O$
Chenevixite	$2CuO.Fe_2O_3.As_2O_5.2H_2O$?	Olivenite	$4CuO.As_2O_5.H_2O$
Chrysocolla	$CuO.SiO_2.nH_2O$	Pickeringite	$MgO.Al_2O_3.4SO_3.22H_2O$
Copper pitch ore	Mixture of Cu, Fe, Mn, and Si oxides	Plumbojarosite	$PbO.3Fe_2O_3.4SO_3.6H_2O$
Darapskite	$3Na_2O.N_2O_5.2SO_3.2H_2O$	Salesite	$CuIO_3(OH)$
Epsomite	$MgO.SO_3.7H_2O$	Metasiderona-trite	$Na_4Fe_2(SO_4)_4(OH)_2.3H_2O$
Ferrinatrite	$Na_3Fe(SO_4)_3.3H_2O$	Soda niter	$Na_2O.N_2O_5$
Goethite	$Fe_2O_3.H_2O$	Tamarugite	$Na_2O.Al_2O_3.4SO_3.12H_2O$
Gypsum	$CaO.SO_3.H_2O$	Ungemachite	$Na_8K_2Fe(SO_4)_6.10H_2O$
Halite	NaCl	Wulfenite	$PbMoO_4$
Halotrichite	$FeAl_2(SO_4)_4.22H_2O$		
Leightonite	$CuO.K_2O.2CaO.4SO_3.2H_2O$		

concentration, antlerite from those of moderate SO_3 concentration, brochantite from low, and cuprous oxide from solutions of very low SO_3 content. Over intermediate ranges of concentration, two of these minerals may be stable together.

(2) In the system Fe_2O_3–SO_3–H_2O at 50° C., also shown in Fig. 1, slight concentrations of SO_3 render stable borgstromite, a mineral similar to jarosite. Increasing concentration of SO_3 produces stability for a number of hydrous ferric sulphates, which, although similar to compounds found in nature, are not identical except in the case of copiapite, kornelite, and rhomboclase. This is perhaps due to the relatively high temperatures employed in the experiments, since it has been demonstrated that the stability fields of several of the natural ferric sulphates do not extend to 50° C.[4]

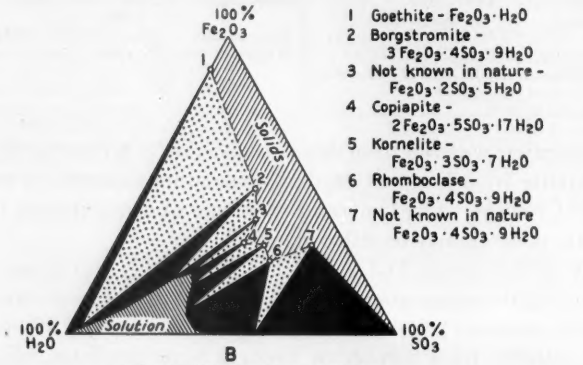
(3) In the four component system, CuO–Fe_2O_3–SO_3–H_2O, tenorite is only stable in contact with solutions of very low SO_3

[4] Merwin, H. E. and Posnjak, E.: Sulphate incrustations in the Copper Queen Mine, Bisbee, Ariz. Amer. Min. *22*: 567–571, 1937.



A

50° ISOTHERM OF THE SYSTEM
CuO · SO3 · H2O (Posnjak and Tunell)


100% Fe2O3
Solids
Solution
100% H2O
100% SO3
1 Goethite – Fe2O3·H2O
2 Borgstromite – 3 Fe2O3·4 SO3·9 H2O
3 Not known in nature – Fe2O3·2 SO3·5 H2O
4 Copiapite – 2 Fe2O3·5 SO3·17 H2O
5 Kornelite – Fe2O3·3 SO3·7 H2O
6 Rhomboclase – Fe2O3·4 SO3·9 H2O
7 Not known in nature Fe2O3·4 SO3·9 H2O

B

50° ISOTHERM OF THE SYSTEM
Fe2O3 · H2O · SO3 (Posnjak and Tunell)

FIG. 1. Explanation of diagrams. Each vertex represents 100 per cent of one of the components of the system, so that any combination of the three can be found at some point within the triangle. Within the area marked "Solution" all constituents are in solution; within the area marked "Solids" all are solids. In between, in the shaded and stippled areas, crystals and liquid are both stable together. At any point in the shaded triangles, the solid deposited would have the composition of the numbered dot at the upper vertex of the triangle, in a solution line drawn through the upper vertex and the point. At any point in the stippled triangles, solids of composition given by the numbered dots at the upper two vertices are stable in contact with a solution whose composition is given by the lower vertex.

and Fe_2O_3 content. In fact, even though the solutions contain considerable SO_3 and CuO, a small amount of Fe_2O_3 prevents development of antlerite, brochantite, or any other copper minerals over the concentrations investigated. However, the experiments were not performed with sufficiently high concentrations of SO_3 to determine definitely the effect of Fe_2O_3 on the precipitation of chalcanthite, although presumably its formation would also be inhibited.

(4) As the CuO concentration increases in the four component system, goethite and borgstromite will precipitate from solutions of increasing H_2O content.

(5) The presence of free sulphuric acid, resulting from the oxidation of pyrite, retards the conversion of ferrous to ferric iron, and thus hinders the deposition of the more stable ferric minerals. On the other hand, the presence of cupric sulphates formed from oxidizing copper sulphides promotes the oxidation of ferrous sulphate and thus tends to fix the iron in place as the more stable hydrous ferric minerals. Both of these factors, plus that referred to under (4) above, show that the presence of copper sulphides in an oxidizing orebody promotes the precipitation *in situ* of iron derived from pyrite.

(6) A gangue of sericite or quartz has less neutralizing effect upon solutions than feldspathic gangue, and thus less tendency to fix copper in the capping.

A number of considerations prevent direct application of some of the laboratory work to the paragenesis of oxidized minerals. The solutions of oxidizing ore deposits are manifestly of more complex composition than those investigated in the laboratory. This is especially significant since the presence of a component in very minor concentration, such as iron in the four-component system investigated, may prevent the crystallization of the major components. Moreover, the experiments of the Geophysical Laboratory were performed at a minimum temperature of 50° C., since at the prevailing low temperatures of oxidizing orebodies, equilibrium is not attained for years. Thus the natural processes might be expected to resemble only approximately the results in-

dicated by the investigation of simple closed systems at higher temperatures in the laboratory.[5] Notwithstanding, as is subsequently apparent, many features of the oxidation at Chuquicamata are explained by the studies of artificial systems.

GENERAL GEOLOGICAL FEATURES AT CHUQUICAMATA.

Location and Physiography. A general description of the ore deposits at Chuquicamata has been published by Taylor.[6]

Northern Chile is physiographically divisible into three northward-trending units, all possessing the common characteristic of extreme aridity. The four thousand-foot wall of the Cordillera de la Costa rises abruptly from the Pacific and consists principally of sedimentary and volcanic rocks, and small granitic intrusives. The crest of the coast range is seldom more than ten miles from the ocean. It is succeeded to the east by the Central Valley of Chile, which in the Atacama Desert is not so much a well-defined valley as a flattening of the slope in the general rise of the country from the Pacific to the first crest of the Andes, one hundred miles inland. This tilted tableland is studded with residual mountain ranges which rise like islands from a vast sea of Quaternary residual, lacustrine, and fluviatile debris. It is a land of optical illusion: immense lakes with mountains floating in them beckon from a distance, automobiles appear to coast uphill, and the mine

[5] In a personal communication, dated October 13, 1942, Dr. George Tunell writes: "The diagrams (see Fig. 1) tell accurately what happens, for example, to an aqueous solution of ferric sulphates and sulphuric acid when the excess acid is gradually neutralized and precipitated by aluminum silicate. The three conditions presupposed by the diagrams are that equilibrium is maintained at all times—which is nearly realized in the oxidation process—and that only the components shown are present in the solution—which unfortunately is not the case—and that the temperatures are those indicated on the diagrams. The second condition not being realized results in the formation of jarosite instead of $3Fe_2O_3.4SO_3.9H_2O$. However, the jarosite field in the system K_2O–Fe_2O_3–SO_3–H_2O probably approaches the $3Fe_2O_3.4SO_3.9H_2O$ field in the limiting Fe_2O_3–SO_3–H_2O system. The changes in the diagrams in passing from the 50° C. to 25° C. are undoubtedly very slight as regards the basic sulphates, but may be appreciable in respect to the normal sulphates."

[6] Taylor, A. V., Jr., Ore deposits at Chuquicamata, Chile. XVI Inter. Geol. Cong. 2: 473–484, Washington, 1935.

dumps at Chuquicamata, actually level, seemingly tilt as much as five degrees from the horizontal.

At lower altitudes, in the Nitrate Pampa to the west of Chuquicamata, are the widespread deposits of nitrate with iodine which have played such an important role in world affairs. In the residual desert ranges, where the late Mesozoic and early Tertiary sedimentary and volcanic rocks are invaded by granitic intrusives, mineral deposits of several types are found.

Chief among these is the copper deposit at Chuquicamata, situated on the west side of a long northward-trending ridge that forms the eastern edge of a huge area of elevated pampa which is enclosed by a large horseshoe bend of the Rio Loa. The climate here is extremely arid. Although rain or snow have fallen several times during the last few years, the records of the past show several years devoid of precipitation.

About thirty miles to the east of Chuquicamata is the main front of the Cordillera Occidental de los Andes, the third physiographic division of Northern Chile. It consists of a mass of volcanic rocks, chiefly Pliocene to Recent in age, on which are perched a line of majestic, more or less isolated volcanos which rise to altitudes of more than 19,000 feet above sea level. Some of these still occasionally show signs of activity. The boundary between Chile and Bolivia follows the crest of the range in this area.

Rock Elements. In this part of the Atacama Desert a thick series of volcanic flows overlie conformably [7] a sedimentary series, which, although unfossiliferous near Chuquicamata, is dated as upper Jurassic by correlation with similar fossil-bearing rocks south of the alluvium-filled Calama Basin. The flows and sedi-

[7] W. S. March, Jr., Chief Geologist, Chile Exploration Copper Company, wrote in personal communication on May 17, 1939: "There is some question about this (referring to the apparent conformity of the volcanics and sedimentary rocks). In general the Jurassic sediments are overlain by red and green shales, derived from andesitic debris, which probably are of late Cretaceous age. Above the shales are Tertiary andesitic volcanics. From exposures I have seen, I am inclined to believe that an erosion interval separates the Jurassic sediments from the Cretaceous (?) shales and another interval the shales from the volcanics."

mentary rocks form a broad anticline trending northeast to southwest into the crest and eastern limb of which the Chuquicamata batholith was intruded. The copper deposit is near the southeastern contact of the batholith, which in this area is predominantly a soda-granodiorite, although there are minor facies of quartz diorite, and even diorite, quartz monzonite, granite, and aplite. On the eastern side of the open pit and to the south, the older intruded rocks are exposed. These consist of hornblende andesite flows with sandstones and shales, and some porphyry of probable intrusive origin.

Kaolinization is widespread in the district due to the acceleration given to weathering by the high sulphate content of waters moving through the rocks. Because of their relatively inert nature, the sedimentary rocks have not undergone a great deal of hydrothermal alteration except local silicification due to contact metamorphism. In contrast, the hornblende andesites and the porphyries have been intensely propylitized. Epidote and chlorite are abundant, and calcite and titanium oxides are common. The plagioclase is sericitized. The alteration is much more prominent in the aforementioned rocks than in the granodiorite, and thin sections of a narrow elongated inclusion of the hornblende andesite show the propylitic alteration to be intense, whereas the adjacent granodiorite is unaltered. Since the granodiorite beyond the limits of the mine is essentially unaltered, the propylitic alteration may have been caused by the intrusion of the granodiorite, or it may have occurred earlier.

Primary Mineralization. The most important structural element of the Chuquicamata district is a strong fault on the west side of the ore deposit, known as the West Fissure (Fig. 3), which forms approximately the hanging wall of the orebody, and separates fresh granodiorite on the west from extremely sericitized and silicified rock with mineralization on the east. This strong break is considered to have been the main channelway for the rising mineralizing solutions. In addition to the West Fissure, other strongly mineralized northward-trending major zones lie to the east and probably served as separate centers of mineralization.

The solutions spread out from these main north-south zones along veins striking northeast to east, and to a lesser extent along northwest striking fractures. So complete was the process of mineralization that the final result was an intricate network of veins, with tiny stringers and disseminations in the rock between the main veins.

At the present time the mineralogy of the hypogene ore is known only from drill hole cuttings, from a few exposures in the open pit, and from some mines on the larger veins, which, however, are now almost inaccessible. The mineralization evidently extended over a long period of time, during which its character and intensity varied considerably at different times and places. An early barren quartz phase with minor molybdenite was concentrated adjacent to the West Fissure. At a later stage abundant pyrite, and then enargite were deposited in the same area, although almost barren pyrite underlies most of the northern end of the deposit. Disseminated pyrite and chalcopyrite are typical of some of the drill holes in the southeastern section of the pit. Most characteristic of the northeast sections are pyrite veins with enargite and some tennantite and primary covellite. Here quartz and alunite are common gangue minerals. As indicated later, this heterogeneity of the primary ore profoundly influenced oxidation and enrichment.

Rock Alteration Associated with the Mineralization. The nature and intensity of rock alteration also vary in different parts of the deposit. The widespread prophylitic alteration of the hornblende andesite and of the porphyries, previously described, probably was not directly connected with the ore mineralization. Within the ore deposit itself the first stage of alteration was the development of orthoclase and, to a lesser extent, quartz phenocrysts and general silicification, which transformed the granodiorite into a tight impermeable rock of quartz monzonite composition.[8]

[8] Evidently this development of orthoclase is comparable to that at Ajo. Gilluly, James: Geology and ore deposits of the Ajo quadrangle, Arizona. Ariz. Bur. of Mines, Geol. Ser. 9, Bull. 141 36–37, 79–80.

This rock, further sericitized and silicified, is now exposed in a broad, irregular belt through the center of the mine.

To the west of the belt of quartz monzonite, the rock is almost completely converted to an aggregate of sericite and quartz which in the bench mapping is termed "sericitite." Quartz is present both as numerous sharp-walled, interlacing veinlets, and in finely disseminated form producing general silicification.

To the east the quartz monzonite gradually grades into chloritized granodiorite in which the ferromagnesian minerals have been converted to chlorite and epidote, and the plagioclase grains are sericitized.

For descriptive purposes the alteration has been divided into three distinct types; actually, however, gradational boundaries are the rule and the different types overlap. Thus the development of secondary quartz monzonite probably originally extended into the area that is now completely converted to sericite and quartz. Moreover, the approximate agreement existing between the alteration boundary of dominantly sericitized rock and dominantly chloritized rock, and the contact between granodiorite and quartz monzonite is probably fortuitous.

During oxidation these different rock units of varying composition and permeability were also important elements in regulating the fixation of iron and copper.

THE GROUNDWATER AT CHUQUICAMATA.

Relation of Top of Sulphides to Water Table. The exact delineation of the present water table is difficult. At the northern end of the mine most of the prospect drill holes were not drilled deep enough to encounter water, and in many holes, especially the early ones, water was not always recorded. During thirty years of prospect drilling the natural fluctuations of the water level have been accentuated by changes resulting from mining, hence adjacent holes drilled at different times often show wide discrepancy in the position of the water table. And within short periods of time the water table fluctuates considerably, especially in the upper parts of the mine. Upon completion of a hole, the standing water

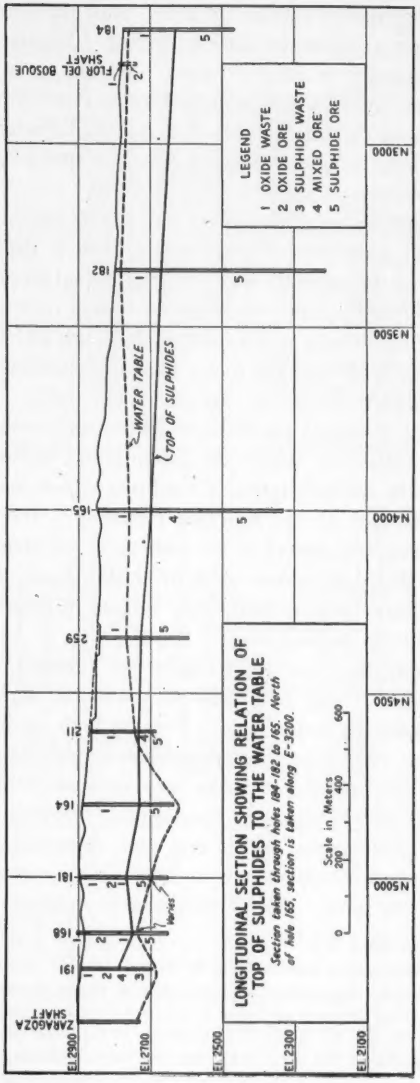

LONGITUDINAL SECTION SHOWING RELATION OF TOP OF SULPHIDES TO THE WATER TABLE
Section taken through holes 184-182 to 165. North of hole 165, section is taken along E-3200.
Scale in Meters
0 200 400 600
LEGEND
1 OXIDE WASTE
2 OXIDE ORE
3 SULPHIDE WASTE
4 MIXED ORE
5 SULPHIDE ORE
WATER TABLE
TOP OF SULPHIDES
FLOR DEL BOSQUE SHAFT
ZARAGOZA SHAFT
Raises
184
182
165
259
211
164
181
168
191
N5000
N4500
N4000
N3500
N3000
EL 2900
EL 2700
EL 2500
EL 2300
EL 2100

FIG. 2.

may be twenty meters higher or lower than the level at which water was first encountered during drilling. Similar conditions have been reported at Ray, Arizona.[9] Hence it is difficult to decide what elevation should be used for the water level in a particular hole, and the information obtained by correlating the reported elevations in holes drilled at different times leads to even greater uncertainty.

Notwithstanding, an approximate water table can be determined with sufficient accuracy to demonstrate that it departs widely from the top of the sulphide ore. A longitudinal section (Fig. 2) through the orebody shows oxidation extending over one hundred meters below the present water table at the south end of the mine, whereas at the north end the lower limit of oxidation may lie at an equal distance above the present water table. The cross-sections (Figs. 3 and 4) show this condition to prevail across the orebody, regardless of where the longitudinal section is taken. Incidentally, the sections reveal a condition which may be rather general in this part of the Atacama Desert, *i.e.*, the water table rises to within a few meters of the surface in the arroyo bottoms, but towards the high pampa north of the mine, or east into the hillside, the water table actually may decline in elevation instead of rising with the surface slope.[10]

It is unlikely that oxidation capable of forming an oxidized orebody (Fig. 3), and removing all traces of sulphides, could take place below the water table. Located high on the side of a residual range, erosion at Chuquicamata—with consequent lowering of the water table—must have been sufficiently rapid to keep new sulphides always exposed to oxidation. Furthermore, except for high sulphide peaks which are later discussed, the top of the sulphides is a comparatively smooth surface, especially at the south end of the mine. Such a condition is suggestive of deriva-

[9] Locke, A.: op. cit., p. 47.

[10] Similar conditions have been observed by the writer in the El Abra mining district north of Choquicamata, and on an examination of copper deposits at Toquepala and Quelleveco in the Province of Tacna in southern Peru. In these districts, preliminary exploration also has indicated that the top of the water table may be at a lower elevation under the hill slopes than under the canyon bottoms.

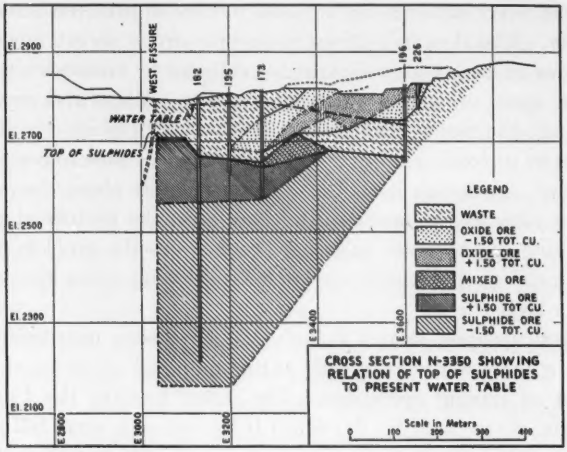


FIG. 3.

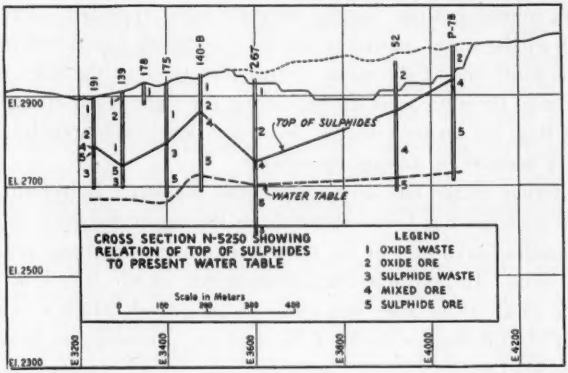


FIG. 4.

tion from an old water level, and precludes the supposition of sub-water oxidation along fissures. Therefore, recourse to recent differential movements in the water table must be made in order to explain the submerged top of the sulphide zone at the south end of the mine, as well as the presence of sulphide marooned high above the water table at the north end.

One recent event readily explains, at least in part, the latter condition. The Atacama Desert in comparatively recent times was an area of more humid climate, as evidenced by buried forests and large areas of lake and stream deposits. With a decrease in rainfall, the water level presumably sank. Sulphide ore left in the zone of oxidation has not yet had sufficient time to completely oxidize. Although it explains the sulphide ore above the present water table at the north end of the mine, the postulated recent lowering of the water table only complicates the problem at the south end where the sulphide ore is considerably below the present water level.

Most apparent among factors that have been instrumental in raising the water level recently at the south end of the mine is the effect of mining operations. The water level in the Flor del Bosque shaft (see Fig. 2), which is located on a small hill at the south end of the mine, is twenty-one meters higher than it was before extensive pit operations began, and just west of the shaft, in the arroyo bottom, springs recently have appeared. Probably much of the water wasted in mining operations has found its way to the south end of the mine. Since almost all of the holes in this section of the mine were drilled during the eight years immediately preceding the writer's study, the water level undoubtedly stands higher because of mining operations.

Another factor has been differential erosion. In recent times much material has been eroded from the upper hillsides, whereas the southwestern part of the mine has remained perhaps almost at base level. In addition, the accumulation in the Rio Loa Basin to the south of an unknown thickness of gravel, which extends to about 1½ kilometers south of the open pit, probably has raised the water level in the southern section of the mine. Isostatic adjustment—if it is possible over so local an area—caused by the filling in of this basin, or tilting due to other causes of which Mr. March reports abundant evidence near Calama, may have accentuated the differential erosion just described.

To summarize, there is little or no justification for assuming that oxidation at Chuquicamata took place below the water table,

and the discrepancy between the top of the sulphide zone and the present water table may be assigned instead to various recent changes that have taken place in the position of the water table. Moreover, these changes have lacked uniformity resulting in the local drowning of the oxidized zone, and elsewhere the projection of sulphides above the water table.

Composition of the Groundwater. The solutions of the vadose zone that effected the oxidation of the Chuquicamata sulphide ores eventually mingled with the groundwater. Hence the groundwater analyses given in Table 2 afford a clue as to the nature of the waters in the zone of oxidation. The latter, however, must have been of a less uniform nature, and in many cases charged with considerably more dissolved material.

All of the analyses are essentially similar in the relative proportions of the different constituents and, with the exception of the samples from the mine shafts, in the total amount of dissolved material. Sulphate is the most abundant acid radical, with nitrate and chloride present in about equal amounts, and silica least abundant. Of the bases, sodium is the most common, calcium and magnesium are about equal, and potassium least concentrated.

Sulphate, chlorine, and nitrate are generally abundant in the groundwaters of arid regions, although the nitrate here is unusually high, and the oxidation of sulphides has enhanced the sulphate content. The sodium has been derived from the decomposition of the sodic rocks of the area during oxidation. Calcium originates in the anorthite molecule of plagioclase feldspar. The low potash content may reflect the resistance of orthoclase to alteration as compared to plagioclase feldspar, as well as the fact that much of the potassium is fixed as jarosite, one of the most abundant minerals of the oxidized zone. Magnesium perhaps came chiefly from the alteration of hornblende and biotite, as did also the small quantity of manganese. The low aluminum content indicates that most of it was retained in kaolin. Copper and iron, the two principal elements supplied by the oxidizing orebody, vary considerably in abundance.

TABLE 2.

ANALYSES OF CHUQUICAMATA GROUNDWATER IN PARTS/MILLION (APPROX.).

	Rosario Mine Level No. 180 May 27, 1932	Panizo Shaft Level No. 4 June 9, 1932	Panizo Shaft Jan. 30, 1930	Hole 151 Jan. 30, 1930	Hole 70 30.7 M. from Collar Mar. 22, 1930	Hole 70 191.2 M. from Collar Mar. 22, 1930	Hole 158 28 M. of H_2O in Hole Mar. 17, 1930	Hole 157 14 M. H_2O in Hole Mar. 17, 1930	Hole 56 Before Bailing	Hole 56 After Bailing Representing New Flow
SO_4	16,440	19,780	9,785	7,832	7,849	8,665	8,921	8,248	7,995	8,405
Cl	870	2,130	605	280	995	936	905	910	860	930
NO_3	2,840	1,470	541	377	672	1,062	745	796	*	*
SiO_2	—	—	55	44	114	—	—	—	—	—
Na	4,100	7,800	3,449 Mostly Na	2,773 Mostly Na	—	—	—	—	—	—
K	150	100			—	—	—	—	—	—
Mg	880	800	352	425	480	488	484	480	*	*
Ca	460	440	496	421	467	476	458	433	—	—
Fe	100	2,060	794	443	101	510	326	360	*	*
Cu	1,150	190	348	472	353	32	987	295	366	1,036
Mn	30	30	—	—	—	—	—	—	*	*
Mo	—	—	6	—	11	14	13	9	—	—
Free Acid (Calculated as H_2SO_4)	250	40	40	40	60	60	60	80	—	—

* Present but not measured.

OXIDATION OF VARIOUS TYPES OF SULPHIDE ORE.

Several different types of oxidation can be clearly deduced from the relations seen within the open pit, and from the churn drill hole cuttings. A study of these relations gives the clue to the origin of the main oxidized orebody of antlerite.

Chalcocite in the Absence of Pyrite. The churn drill cuttings and pit exposures rarely disclose complete replacement of the ubiquitous pyrite of the primary ore by supergene chalcocite, so that—at least for the present top of the sulphides—oxidation generally results in the production of considerable sulphuric acid and iron sulphate in proportion to cupric sulphate. This oxidizing environment in most cases prevented the formation of cuprite or native copper. However, one of the holes on the eastern fringe of the orebody has a thin chalcocite zone with little pyrite just at the top of the sulphides. This chalcocite oxidizes directly to cuprite. Similarly, in Hole 196 (Fig. 3) on the southeastern edge of mineralization there were large quantities of native copper in the middle of a thick section of otherwise barren capping. The native copper probably is also the result of oxidation of a rich vein zone of chalcocite, with low pyrite content and consequent lack of adequate oxidizing agents.

However, despite the general evidence of incomplete enrichment in the sulphide ore exposed to oxidation at the present time, nodules and veins of pure chalcocite sometimes occur on the east side of the lower benches. Pyrite is commonly entirely absent, in which case chalcocite alters directly to antlerite. It is interesting to note that this alteration takes place in the center of the orebody where, although oxidizing pyrite is locally absent, the general concentration of sulphuric acid and iron sulphate in the immediate vicinity must be comparatively high.

Thus it seems that on the eastern fringe of the mineralized zone pyritic ore completely enriched to chalcocite locally alters to cuprite or native copper, whereas pure chalcocite in the center of the orebody where the sulphuric acid concentration is higher oxidizes directly to antlerite.

Disseminated Chalcocite and Pyrite. In this type of mineralization, the proportion of chalcocite to residual pyrite is the controlling factor in determining the end results of oxidation. If the pyrite content is high, copper minerals do not occur in the immediate vicinity and powdery jarosite is the only material left in place of the sulphides. On the other hand, if chalcocite is more abundant, or the ore is of more disseminated character, chalcanthite and in some instances antlerite are produced besides limonite and jarosite. These copper minerals, however, are not found directly in place of the sulphides but instead occur in the wall rock at varying distances from them. In short, the amount of oxidized copper minerals formed and their proximity to original sulphides depends upon the chalcocite-pyrite ratio in the sulphide ore.

Evidently a mixture of pyrite and chalcocite with dominant pyrite oxidizes to yield a high concentration of ferric iron which inhibits precipitation of copper minerals, whereas the presence of copper sulphides promotes the precipitation of the iron in place as jarosite or limonite, first, by increasing the rate of oxidation of ferrous to ferric iron, and second, by decreasing the solubility of the ferric minerals. Requisite potassium for the formation of jarosite is liberated during kaolinization of the wall rock resulting from sulphuric acid attack. Upon precipitation of the iron as jarosite directly in place of the sulphides, copper is then free to deposit in the wall rock. Since the sulphate content of the solutions is still high, only a portion having been fixed as jarosite, chalcanthite generally results; on the other hand, if the acid concentration is lower because of lower pyrite content of the sulphide ore, antlerite may accompany the chalcanthite.

Pyrite Veins. In the northeast corner of the pit the sulphide mineralization is chiefly localized in strong veins striking northeast and north. The primary mineralization of these veins is massive pyrite with only minor lenses and shoots of associated enargite. Supergene enrichment has increased the copper content only slightly, hence in the veins as exposed to oxidation pyrite predominates. The deposits at Quetena and Alcaparossa [11] are

[11] Bandy, M. C., op. cit.

mineralogically similar to the pyrite veins of Chuquicamata, but the orebodies are more lens-shaped or pipe-like in form. Such massive pyritic ores oxidize to yield an unique assemblage of hydrous iron sulphates which are formed in rather definite order as concentric rings around kernels of unoxidized pyrite. Ideally, roemerite and voltaite form adjacent to pyrite, succeeded by rings of rhomboclase and coquimbite, and in turn, copiapite and jarosite. However, where the pyrite mineralization is less massive, either the first or both the first and second rings may be lacking. Amarantite, castanite, and fibroferrite are other simple ferric sulphates that may form locally. Also, the ferric and alkali sulphates may be present in the veins, namely, sideronatrite, metavoltine, ferrinatrite, botryogen, and ungemachite. Copper minerals are not common although there may be some chalcanthite or krohnkite, or more rarely except at Quetena, cuprocopiapite.

The reason for this succession is readily apparent from the first part of Table 1 and the second diagram in Figure 1. Roemerite and voltaite form first if pyrite is very abundant since both excess sulphuric acid and the lack of copper retard the oxidation of ferrous to ferric sulphate long enough for these two ferrous sulphate-bearing minerals to deposit. Rhomboclase, coquimbite, and copiapite next become stable more or less in that order because of their high SO_3 content. The equilibrium diagram in Figure 1 shows that the Fe_2O_3–H_2O ratio may vary quite widely without having any control over the composition of the solid phases in equilibrium. A much smaller change in the SO_3 content, however, will affect the stability relations. Evidently in these deposits also the SO_3 content similarly determined which minerals should form, and in what order. Amarantite, castanite, and fibroferrite accordingly were deposited when the acid concentration had become slightly lower, although probably because their stability fields do not reach 50° C., they are not represented in Figure 1. Similarly kornelite has a very narrow stability field at low temperature,[12] which probably explains why it has not been found at Chuquicamata.

[12] Merwin and Posnjak: op. cit., p. 570.

The production of such large quantities of sulphuric acid resulted in extensive leaching of alkalis from the wall rock, and the alkalis so introduced into the system caused the precipitation of various alkali ferric sulphates. The predominance of minerals with sodium and potassium, the two principal alkalis in the wall rock at Chuquicamata, is to be expected.

As in the disseminated pyrite-chalcocite ore, oxidized copper minerals could not form in these veins until the iron had been fixed, following which some chalcanthite was deposited. Most of the copper, however, migrated into the wall rock where it precipitated at some distance as krohnkite, natrochalcite, or chalcanthite.

Enargite. If enargite is present in the oxidizing sulphides, copper arsenates, generally chenevixite,[13] locally with olivenite, may replace the enargite directly. In some cases, however, the arsenic probably goes into solution and passes beyond the limits of the orebody without again being precipitated. Nevertheless, when arsenates are found in the oxidized orebody, a corresponding amount of enargite may be expected in depth.

Sulphides Close to the Surface. The primary sulphide mineralization was accompanied by sericitization, silicification, and alunitization which locally converted the granodiorite and quartz monzonite into hard, tough rocks. The altered rocks in many areas resisted post-mineral fracturing and consequently shielded the enclosed sulphides from oxidation, even though these zones were marooned high above the water table. This was the origin of the sulphide peaks which project far up into the oxidized ore, and which are exposed at the present bench levels, especially in the center and at the north end of the mine. In some places the sulphides have been observed within 20 meters of the ground surface, although in general the top of the sulphides lies over 125 meters from the surface.[14]

[13] The identity of chenevixite has not been proved. The material known as chenevixite at Chuquicamata is an amorphous light green mineral, analyses of which correspond approximately with the formula of chenevixite.

[14] The cross sections on coördinates N. 4800 and N. 5250, in the previous reference by Taylor, provide a clear picture of these sulphide peaks.

Near the surface these peaks eventually yield to oxidation, and krohnkite, or more rarely natrochalcite, forms with or in place of chalcanthite in the vicinity of the sulphides. Jarosite and limonite are, as usual, the iron precipitates. Generally also minerals high in sulphate and containing alkalis, such as mirabilite, blodite, and epsomite, are deposited and the rock is much kaolinized. The Teodora and San Luis-Balmaceda vein zones provide good examples of high sulphide peaks cut by the present pit.

SECONDARY CHANGES IN THE ZONE OF OXIDATION.

After description and interpretation of the oxidation of the various types of sulphide ore, there remain for discussion three classes of oxidized ore which are not directly related to the underlying sulphide mineralization.

Conversion of Chalcanthite, Krohnkite, and Natrochalcite to Antlerite, and Antlerite to Brochantite. As heretofore stated, antlerite may form directly from chalcocite, or if pyrite is not too abundant, it may form with chalcanthite in the wall rock adjacent to oxidizing sulphide ore. In addition, where not too near the surface, chalcanthite and commonly also krohnkite and natrochalcite become unstable only a few meters from oxidizing sulphides and are transformed generally to antlerite. Such is the normal trend of the oxidation observable in the present pit, *i.e.*, first, the oxidation of pyritic ore leaving jarosite and limonite in place, with chalcanthite being deposited close by, and later the conversion of chalcanthite to antlerite.[15]

At greater distances from oxidizing sulphides even antlerite is seemingly unstable and gives way to brochantite. The few specimens of brochantite that have been found come from either the fringes of the orebody, or if in the center, from high above the top of sulphides.

The Tunell-Posnjak diagram given in the first part of Figure 1 shows that the paragenesis of the hydrous copper sulphates is essentially controlled by the SO_3 concentration, for similar to the

[15] Mr. Reno Sales, in a private report to the company in 1930, was the first to recognize this succession.

system Fe_2O_3–SO_3–H_2O, the CuO–H_2O ratio may vary considerably without changing the triangle in which the point representing the total composition of the system falls, while a relatively small change in the SO_3 concentration places the point in a different triangle. The second part of Table 1, which gives the relative composition of some of the copper minerals, shows how closely the succession that might be deduced from the decreasing proportion of SO_3 follows the actual paragenesis that has been described.

The localization of the oxidized copper minerals of the deposit along post-mineral fractures and joint planes shows that few of them formed directly in place of sulphides. As mentioned previously, the presence of iron is responsible for this migration; however, as soon as the iron becomes fixed as limonite or jarosite, copper minerals are free to precipitate and the principal factor that then controls the specific copper mineral deposited is the SO_3 content. The feldspar content of the quartz monzonite, in which the oxidized body mainly lies, depletes SO_3 by base replacement and thus only a few meters from oxidizing sulphides the SO_3 concentration is so reduced that chalcanthite, natrochalcite, and krohnkite become unstable and antlerite takes their place. Similarly at much greater distances from the source of the SO_3, and generally where the wall rock is chloritized granodiorite with little sericitization, the solutions become sufficiently impoverished in SO_3 that brochantite or even CuO (melaconite) may form.

Minerals Stable on the Fringes of the Orebody. Cuprite and native copper have been mentioned previously as forming from isolated occurrences of chalcocite on the periphery of the orebody. In addition, a variety of other oxidized copper minerals occurs here, commonly in chloritized or fresh granodiorite, and not underlain by sulphide ore. Hence this type of ore is "exotic" and is apparently similar to occurrences that have been described in the Globe-Miami District.[16]

[16] Tenney, J. B.: The copper deposits of Arizona. XVI Inter. Geol. Cong., vol. 1, p. 200, Washington, 1935.

Among these oxidized minerals are atacamite, copper pitch ore or melaconite, and several different amorphous copper silicates that have been grouped together under the name chrysocolla. There are also thin green and bluish films which coat joint planes and which in mapping are designated as copper staining, although their composition has not been determined. The first-named minerals are further characterized in this area of the mine by their nodular habit.

Evidently on the fringe of the orebody the remoteness from oxidizing pyrite and the greater neutralizing character of the wall rock reduced the SO_3 content of the solutions migrating outward from the center of mineralization to a point where other copper minerals in addition to copper sulphates might form.

Minerals Formed Close to the Surface. Within a few meters of the surface over oxidized ore a variety of alkali sulphates, nitrates and chlorides is found. Gypsum, blodite, mirabilite, epsomite, and darapskite are most common, but halite, soda niter, pickeringite, halotrichite, and tamarugite also have been recognized, and there are undoubtedly others.

Copper is partially leached here, antlerite is generally unstable, and commonly atacamite and krohnkite and, in places natrochalcite, or even chalcanthite, take its place. The very rare occurrences of the copper-iodine minerals marshite, salesite, and bellingerite [17] are confined to this near-surface zone. Numerous assays for chlorine have shown that atacamite, which is the only common chlorine-bearing mineral of the orebody, is entirely limited to within about 30 meters of the surface. The SO_3 concentration evidently does not affect the deposition of atacamite since it may be found on either the very fringes of the oxidized orebody or over the center, associated with krohnkite and other minerals indicative of high SO_3 content.

[17] Jarrell, O. W.: Marshite and other minerals from Chuquicamata, Chile. Amer. Min. 24: 629–635, 1939. Palache, Charles and Jarrell, O. W.: Salesite, a new mineral from Chuquicamata, Chile. Amer. Min. 24: 388–392, 1939. Berman, Harry and Wolfe, C. W.: Bellingerite, a new mineral from Chuquicamata, Chile. Amer. Min. 25: 505–512, 1940.

Leightonite commonly occurs in this surface zone, and also lindgrenite if underlain by sulphide ore containing molybdenite.

Within a few meters from the surface, SO_3 apparently is concentrated again in the solutions, perhaps due to greater evaporation since circulation of both air and solutions is facilitated by increased porosity and permeability in this zone near the surface. This increase in SO_3 content, together with the greater abundance of oxygen, promotes the kaolinization of the country rock and the attendant release of alkalis into solution. In addition, wind-blown sodium chloride from the lower elevations of the Nitrate Pampa may increase the content of sodium and chlorine. Probably this is also the source of the iodine in the aforementioned copper-iodine minerals.

The result is the deposition of the hydrous alkali sulphates earlier described. The SO_3 content is too high for antlerite or brochantite to form, although, because of the high Cl content, atacamite is stable. The high concentration of Na_2O and of SO_3 in this zone would lead to the expectation that krohnkite—the copper mineral highest in these two constituents—would be abundant, which is the case. Natrochalcite and even chalcanthite may be present, but they are always in minor amounts close to the surface. Often even krohnkite is not found, and the presence of a white, extremely kaolinized rock with abundant alkali sulphates is the only clue to rich antlerite ore below.

The similarity in mineralogy and origin of this zone to that already described as formed over the high peaks of sulphide ore is readily apparent.

ORIGIN OF THE MAIN OXIDIZED OREBODY.

Antlerite, which veins and coats the rock in every direction, is almost the only copper mineral in the main oxidized orebody.[18]

Lindgren [19] and others have advanced the opinion that the oxi-

[18] For many years this mineral had been mistaken for brochantite, despite the fact that several independent investigators in the United States and elsewhere had identified specimens as antlerite.

[19] Lindgren, Waldemar: Report on the Chuquicamata Lode. Private report to Chile Exploration Co., 1917.

dized orebody was formed by the oxidation in place under arid conditions of a relatively rich chalcocite-covellite orebody formed by prolonged supergene enrichment. Although there is some conflicting evidence, this still appears to be the most logical explanation.

Several features can not be explained if the original sulphide ore contained much pyrite. The first of these is the scarcity of iron; there is considerably less than would be expected from any ordinary process of oxidation acting upon a pyritic ore. However, alteration of chalcocite directly to antlerite has already been described, and if this occurred to any great extent, there naturally would be little limonite left in the oxidized ore. Another feature of the good grade oxidized ore is the moderate alteration compared with other areas of lower copper content to the west. The rock still retains its texture, and the feldspar crystals, although more or less sericitized and kaolinized, are readily discernible in contrast to the leached capping on the western side of the mine. The only conclusion is that primary mineralization could not have been as intense here, and that the good grade ore must have resulted from intense supergene enrichment.

It is very probable, therefore, that oxidation of supergene chalcocite-covellite ore resulted in the present good grade oxidized orebody of antlerite. Perhaps some pyrite persisted in the sulphide ore and consequently a minor amount of antlerite probably formed through the intermediate stage of chalcanthite. The depression of the water level with the change from a semi-humid to a very arid climate, and the exposure of the chalcocite-covellite body above the water level, was responsible for the formation of antlerite. Some zones and veins which were enclosed by impervious alteration casings were not affected by supergene enrichment. They escaped later oxidation for the same reason, and hence were preserved as the high sulphide peaks which in some instances contain unaltered enargite far above the general level of oxidation.

DESCRIPTION AND ORIGIN OF THE WASTE ZONE OVERLYING SULPHIDES.

On the west side of the mine, as shown by the mine sections (Figs. 2, 3, and 4), drill holes do not encounter any oxidized ore, but instead pass directly from a leached capping containing abundant iron into deep, good grade sulphide ore. A similar waste zone intervenes between the top of sulphides and the oxidized ore throughout much of the mine. Different types of residual iron oxides, jarosite, and especially transported iron oxides are very abundant in this zone. Oxidized copper minerals are often completely absent. The wall rock is principally the 'sericitite' described under rock alteration.

Evidently on the west side of the mine, south of about N. 4650, the primary mineralization, especially the pyrite stage, was most intense. Enrichment, therefore, was not as complete as further to the east, and hence when the water level sank in response to the climatic change, the ore still contained abundant pyrite. The sulphuric acid and the ferric sulphate derived from this pyrite, and the lesser neutralizing ability of the quartz-sericite gangue as compared to the feldspathic gangue of the quartz monzonite further to the east, prevented any copper minerals, even chalcanthite, from depositing. Instead, the cupric sulphate descended to replace the pyrite at greater depths and so yielded the deep supergene enrichment shown by such holes as No. 165 and No. 182 (Fig. 2). Abundant iron oxides were formed and the result was the iron-quartz-sericite capping, barren of oxidized copper minerals, which overlies the good grade enriched sulphide ore.

North of about coordinate N. 4650 on the west side of the mine, the primary mineralization was even richer in pyrite, with very little copper. Consequently the enriched zone, before the lowering of the water table, was still very pyritic, so that its oxidation yielded principally jarosite, and little copper was available to enrich the primary ore in depth. The present enriched zone is, therefore, thin and low grade and underlain by barren pyritic protore.

On the east side of the deposit, and also to a lesser extent in the center, the original supergene enrichment, although pronounced, was shallow, since the protore was low grade and pyritic. Consequently, after the depression of the water table in this region, some ore that had not been enriched previously was exposed to oxidation. The resulting high concentration of ferric iron and low copper in this unenriched zone prevented the fixation of copper. Thus was formed the iron-stained waste zone that separates the thin blanket of sulphide ore from the rich oxidized orebody. This waste zone is thin or missing in the center of the mine, but thickens on the eastern edge.

ZONE OF PARTIAL OXIDATION.

Drill hole cuttings commonly show the upper part of the sulphide ore to have been slightly oxidized to a variable depth. Iron staining and limonite are the principal visible criteria. Although oxidized copper minerals are seldom seen, assays may show sufficient (0.30 per cent) soluble copper to classify the material as mixed ore.[20] Although chalcanthite, which is soluble in the water used in drilling, may be the source of some of this soluble copper, it seems more logical to assume that some soluble copper is retained in limonite formed from chalcocite.

In support of this may be cited assays 3 and 5 given in Table 3, which were made on specimens of red limonite. No oxidized copper minerals or even chalcocite were discernible before assaying. The only explanation is that both the soluble and insoluble copper are absorbed in the amorphous limonite. The high FeO content shows that oxidation is incomplete.

When the fluctuations that have been described in the water table are considered, it is probable that this zone of incomplete oxidation at the top of the sulphides is due to occasional exposure to oxidation but not for sufficiently long periods for the copper to be entirely eliminated.

[20] Recent diamond drilling is demonstrating that this zone of mixed ores is not as extensive as shown by past drilling. However, the mixed ores have by no means been eliminated, and the explanation that is given here for their origin is still considered valid.

TABLE 3.

ANALYSES OF CHUQUICAMATA MINERALS.
(By E. V. Herring)

	(1)	(2)	(3)		(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Jarosite from Branch of C-2 Fissure. West Side C-3 Canal	Jarosite from Unknown Location on D-1	Red Limonite and Pyrite. Sulphide Area in NE Corner Bench F-2		Cellular Gossan Limonite C-1 West Side N. 5003 E. 3564	Red Limonite from Chalcocite-Pyrite D-2 N. 4451 E. 3778	Chal-can-thite	Para-atacamite W. Side of E-2	Antlerite and Atacamite E-3 N. 4455 E. 3400	Antlerite E-1 N. 4510 E. 3400	Chenevixite E-3 N. 4480 E. 3400	Antlerite from Crossfiber Veinlets in Center of Pit	Copper Pitch Ore C-2 N. 4000 E. 3930
			Sample 1	Sample 2									
Ag G/MT....	38.0	9.2	21.2	—	4.4	26.0	None	690	424.0	235.5	222.0	20.4	2.6
Au G/MT....	0.4	Tr.	0.2	—	Tr.	Tr.	None	5.0	1.5	1.0	0.30	0.2	Tr.
Tot. Cu %...	0.26	0.49	10.36	8.17	0.65	8.35	—	47.59	36.88	26.68	13.50	50.05	3.64
Sol. Cu %....	0.06	0.32	7.99	6.30	0.14	8.00	—	46.04	36.62	26.14	3.82	48.90	3.06
Insol. Cu %..	0.20	0.17	2.37	1.87	0.51	0.35	—	1.55	0.26	0.54	9.68	1.15	0.58
FeO %.....	0.04	0.5	5.1	—	1.7	0.3	—	—	—	—	—	—	0.1
Fe_2O_3 %.....	38.0	33.2	47.9	—	29.9	28.0	—	—	—	—	13.7	—	3.1
Cl %.....	0.003	0.082	0.001	—	0.002	0.001	Tr.	13.2	1.58	0.09	Tr	0.002	0.022
SO_4 %.....	14.4	17.0	13.3	—	1.2	7.7	—	—	—	—	None	—	—
S as Sulphide %.....	—	—	11.0	—	—	—	—	—	—	—	—	—	—
As %.....	—	—	0.05	—	0.03	0.06	—	—	—	—	15.20 (Sb 0.27%)	—	Tr.
SiO_2 %.....	—	—	3.8	—	57.7	30.8	—	—	—	—	—	—	58.0
K_2O %.....	5.8	4.1	—	—	—	—	—	—	—	—	—	—	—
Na_2O %.....	1.0	1.8	—	—	—	—	—	—	—	—	—	—	—
Pb %.....	0.019	Tr.	—	—	—	—	—	—	—	—	—	—	—
Mn %.....	—	—	—	—	—	—	—	—	—	—	—	—	5.3
Insol. %.....	17.0	25.8	4.5	—	59.4	42.5	1.0	16.9	26.35	38.60	—	4.3	77.9

Note: With the exception of Ag and Au the assays on the two jarosite samples were performed on the acid soluble portions only.

BEHAVIOR OF THE LESS ABUNDANT ELEMENTS DURING OXIDATION.

Attention up to this point has been focused upon the behavior of Cu, Fe, and As during oxidation; there remain to be discussed Mo, Mn, Pb, Zn, Sb, Ag, and Au. All of these occur in small amounts in the ore. Except for Mo, there is no indication that they have any economic importance in the oxidized ore, and little attention has been paid to their occurrence. Table 3 gives some assays made on oxidized specimens that are referred to in the following discussion.

Molybdenite is normally quite resistant to oxidation; hence where it formed part of the hypogene mineralization at Chuquicamata, residual molybdenite probably exists above the general top of sulphides. When it finally capitulates to the oxidizing solutions, the molybdenum and sulphur go into solution, and a brown limonite remains pseudomorphic after the molybdenite crystals. The molybdenum combines with copper in solution and deposits lindgrenite a few centimeters away; or it may be absorbed by coming into contact with the existing amorphous, extremely porous chenevixite, since assays of the latter mineral show it to contain up to 5 per cent Mo. Near the surface or under exceptional conditions elsewhere, yellow molybdic ochre may form. A very few specimens of wulfenite also have been found.

Manganese has been detected only in the copper pitch ore (see Table 3) which sometimes is found on the eastern limit of the oxidized ore, apparently with no relation to underlying sulphide ore. There is also considerable copper pitch ore, likewise containing manganese oxides, on the dumps of the Zaragoza Vein system. Manganese minerals have not yet been identified in the sulphide ores, and when the small amount of manganese generally present in the groundwater is taken into consideration, it seems that manganese must have come from outside the orebody, perhaps from the decomposition of manganese-bearing ferromagnesian minerals.

Galena occurs very sparingly; it is noted as extremely small isolated grains only in polished specimens of the sulphide ore. The

average lead content of the primary ore probably is to be measured, therefore, in hundredths of one percent. During oxidation lead probably is fixed in place as anglesite, or more rarely as wulfenite. It may be present also as the plumbo-jarosite molecule in jarosite since the two analyzed specimens of jarosite (Table 3) contained, respectively, 0.019 per cent, and a trace of lead. W. S. March, Jr. reports that analyses made some years ago of jarosite from the veins in the northeast corner of the pit showed about 0.1 per cent lead.

Zinc minerals have not been detected in the oxidized ore, although one hand specimen of sphalerite has been found, and sphalerite is noticed frequently in polished sections of the sulphide ore and in drill hole cuttings. Zinc probably was not fixed during oxidation but instead migrated as zinc sulphate outside of the zone of oxidation into the groundwater.

Assays of drill hole composite samples show that antimony is a rare constituent of the sulphide ore. Enargite and tennantite at Chuquicamata contain very little antimony in solid solution. As might be expected, what little antimony is present follows along with arsenic during oxidation. Two analyses of chenevixite show 0.27 per cent and 0.1 per cent antimony, respectively (Table 3).

Silver and gold are very erratic in the oxidized ore. A study of drill hole composite samples has failed to disclose any regularity of vertical distribution. However, some oxidized minerals, especially those occurring on the western side of the mine, contain gold and particularly silver in relatively large quantities. Judging from the assays in Table 3, neither chalcanthite nor copper pitch ore contain gold and silver. Limonite and jarosite are erratic as precious metal carriers, perhaps depending to a large extent upon the sulphides from which they are derived, but they never seem to contain large quantities. The principal carriers of precious metals are antlerite, atacamite, para-atacamite, and chenevixite, particularly where they occur in high grade copper veins on the west side of the mine. Copper minerals in other areas are not as rich in gold and silver, for example, sample No. 11 of Table 3. Furthermore, an average of sixteen analyses made of material that

was handpicked from high grade veins in waste areas on the east side of the mine gave:

Soluble copper	27.2%
Insoluble copper	0.8%
Silver (gms. per metric ton)	31.5
Gold (gms. per metric ton)	0.11

In contrast with this average are samples seven to ten in Table 3, all of which came from veins on the western side of the mine.

The significance of these conditions is not entirely clear. Although drill holes indicate that the gold and silver values of the sulphide ore are higher on the western side of the mine, the difference is not sufficient to account for the much higher content of some of the oxidized copper minerals there. Chenevixite is amorphous and very porous, and many of the other copper minerals in the veins here are fine grained. It appears that these minerals have the property of absorbing gold and silver from percolating solutions.[21] Although the chemistry is not clear, presumably gold must go into solution and migrate in order to form material carrying as much as 5 grams of gold per metric ton (Table 3, No. 7) from the oxidation of sulphide ore of this type.

SUMMARY.

1. The unique character of the mineralogy of the oxidized ore at Chuquicamata is due principally to the arid climate of the region. The results of investigations of artificial systems by the Geophysical Laboratory, Washington, D. C., can be correlated with field observations to show that changes in the mineralogy in different parts of the zone of oxidation at Chuquicamata are due chiefly to variations in the iron and sulphate content of the oxidizing solutions, since differences in the relative concentrations of these two substances are the principal factors that determine which minerals are stable. In turn, the iron and sulphate concentrations are controlled for the most part by the pyrite content of the ore

[21] Work by the writer on specimens from the 'pacos' or oxidized ores of the Cerro de Pasco District, Peru, has shown a similar occurrence of amorphous iron oxides with much higher silver and gold values than the average of the deposit.

undergoing oxidation and by the neutralizing ability of the wall rock.

2. The discrepancy between the top of sulphides and the present water table at Chuquicamata can be explained by recent changes that have taken place in the position of the water table caused by climatic change, pit operations, differential erosion, and the filling in of the Calama Basin. No appreciable amount of oxidation is thought to have taken place below the water table.

The composition of the present groundwater, except for a high nitrate content, conforms to what might be expected from an oxidizing pyrite-chalcocite orebody with a granodiorite wall rock in an extremely arid region.

3. From pit exposures and churn-drill hole cuttings, the following types of sulphide ore as exposed to oxidation, and the attendant variations in the mineralogy of the oxidized ore formed therefrom, have been distinguished:

a. Chalcocite ore containing little or no pyrite and located on the eastern fringe of the area of mineralization occasionally may alter directly to cuprite or native copper, since both the iron and sulphate contents of the oxidizing solutions are very low. In contrast, near the center of mineralization where the sulphuric acid concentration is higher, although the iron remains low, chalcocite oxidizes directly to antlerite.

b. Because iron, if present in the oxidizing solutions, prevents the precipitation of copper minerals in place, the oxidation of *chalcocite and pyrite ore* leaves only iron minerals in place, whereas chalcanthite, and in some instances antlerite, are deposited nearby.

c. The oxidation of *aggregated pyritic ore localized in definite veins* liberates large quantities of sulphuric acid which decomposes the wall rock, thus yielding a complicated succession of sodium and potassium sulphates. Copper minerals are not deposited because of the high concentrations of iron and sulphate in the solutions.

d. Enargite ore in some instances yields chenevixite and other copper arsenates in place, hence the presence of these minerals is indicative of enargite in depth. In other instances, the arsenic

probably goes into solution and is not retained in the zone of oxidation.

e. Due to protective impermeable alteration halos, some *zones of strong sulphide mineralization* escape oxidation until very near to the surface. When oxidation finally takes place, krohnkite and natrochalcite are formed, as well as chalcanthite and alkali sulphates such as mirabilite, blodite, and epsomite.

4. Three additional secondary processes or types of oxidation are also deduced from exposures in the open pit, namely:

a. Because of a decreasing sulphate concentration, antlerite takes the place of chalcanthite, krohnkite, or natrochalcite a short distance away from oxidizing sulphides, and at a still greater distance even brochantite may form.

b. Because of a lowered concentration of sulphate away from the center of mineralization, atacamite, chrysocolla, and copper pitch ore are stable on the fringes of the orebody, and form "exotic" bodies of oxidized ore underlain by barren ground.

c. Within a few meters from the surface over oxidized ore a number of alkali sulphates, nitrates, chlorides, iodates, and iodides are formed due to the decomposition of the granodiorite, the more concentrated nature of the vadose water due to capillary attraction at the surface, and the probable addition of chlorine and iodine by wind transportation.

5. The main oxidized orebody of antlerite was formed by oxidation *in situ* of a chalcocite body previously formed by supergene enrichment of a low grade pyritic protore.

6. The waste zone which overlies sulphides and extends all the way to the surface on the west side of the mine, and the deep underlying supergene enriched sulphide ore of this area, are due to a higher pyrite content of the ore that was oxidized, as well as to the inert gangue of sericite and quartz which was unfavorable to the fixation of copper in the zone of oxidation.

7. Partial oxidation at the top of the sulphides, resulting in mixed oxidized and sulphide ore, is attributed to pronounced fluctuations in the water table permitting some oxidation of the chalcocite to limonite, with retention of some of the copper.

8. Minor elements present in the primary ore and wall rocks include Mo, Mn, Pb, Zn, Ag, and Au. In the oxidation of molybdenite, a brown limonite is left pseudomorphic after the molybdenite, while lindgrenite generally is deposited only a few centimeters away. Manganese has not been detected in the ore minerals, and presumably, therefore, the small percentage of manganese in copper pitch ore has come from outside the orebody. Lead derived from the small amount of galena present in the primary ore has been fixed in place as anglesite, wulfenite, or as a minor constituent of jarosite. Zinc, also rare in the primary ore, migrated beyond the orebody during oxidation. The small amount of antimony in the primary ore followed arsenic during oxidation.

The precious metals are not concentrated in any well-defined horizontal zone of the oxidized ore. Chalcanthite and copper pitch contain very small amounts of gold and silver; limonite and jarosite, although erratic, normally contain larger amounts. Some specimens of chenevixite, atacamite, and antlerite, particularly if from the high grade copper veins on the west side of the mine, contain relatively large amounts of silver and gold. Some solution and concentration of the precious metals must have taken place in order to explain this distribution.

GRAND JUNCTION, COLO.,
Sept. 29, 1943.

CELESTITE IN BUFFALO COVE, FENTRESS COUNTY, TENNESSEE.[1]

THOMAS L. KESLER.

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ABSTRACT.

Mineral aggregates consisting of celestite, dolomite, calcite, and very small amounts of sphalerite, anhydrite, and pyrite occur in the uppermost beds of the Glen Dean limestone, of upper Mississippian age, which crops out along the slopes of Buffalo Cove. Proportions of minerals range widely in adjacent aggregates; maximum content of strontium sulphate is about 96 per cent. The aggregates are spherical to nearly flat, and are regular to irregular in outline; a few coalesce. The maximum dimensions of those examined range from 0.04 to 1.35 feet, and their known vertical range in the Glen Dean limestone is from 7 to 20 feet or more downward from the contact with the overlying Pennington shale. The aggregates in the uppermost beds commonly contain chert and are somewhat hollowed as a result of weathering. Those in the lower beds contain no chert, and, where unweathered, no cavities. Celestite also occurs as isolated crystals and groups of crystals embedded in the limestone. The limetone is fine-grained, brownish gray, argillaceous, and unfractured.

1 Published by permission of The Director, Geological Survey, U. S. Department of the Interior.

The isolated crystals probably were precipitated from connate water as the limestone consolidated. During subsequent erosion of the Pennington shale to a level only 200 feet above the Glen Dean limestone, meteoric water probably gained access to the upper Glen Dean beds and dissolved cavities in them. The dense, unjointed limestone prevented downward percolation of the water, which became saturated with strontium sulphate and calcium carbonate, and deposited celestite and calcite in the solution cavities. As the dolomite in the aggregates has no apparent local source, it is believed to have been introduced from depth, probably with the small amounts of sphalerite and pyrite, by hydrothermal solutions in post-Mississippian time. Although no veins were seen in the few exposures examined around the cove, it is inferred by analogy with other mineralized areas that the solutions rose along fissures and were deflected by the overlying shale, spreading laterally through the partly filled cavities in the limestone without impregnating the limestone itself. Meteoric water still present in the cavities probably promoted deposition without attack on the limestone by lowering the temperature of the solutions.

The celestite zone is being developed at the Youngs quarry. Reserves in the block of ground that contains the quarry are estimated to be 2,822 tons of the mineral aggregates, or strontium ore, containing 2,148 tons of celestite. The celestite constitutes 5.89 per cent by weight of the combined rock and aggregates in the block. Four out of seven exposures examined elsewhere in the ore zone suggest that other roughly comparable blocks may be developed. Underground quarrying is not practicable because of the overlying shale, but a dozen or more similar open quarry sites might be found on the divides between the numerous ravines that drain the sides of the cove.

INTRODUCTION AND ACKNOWLEDGMENTS.

THE inquisitive interest of Ernest Gernt of Jamestown, Tennessee, which led to a blow-torch flame test, recently revealed an extensive occurrence of celestite in Buffalo Cove, north-central Tennessee (Fig. 1). The mineral, known to local residents for many years, had previously been regarded as barite.

Buffalo Cove is a steep-walled valley formed by the dissection of the western margin of the Cumberland Plateau. It is drained by Buffalo Cove Creek which flows westward into the East Fork of Obey River, a tributary of the Cumberland. The plateau has an average altitude of 1,700 feet adjacent to Buffalo Cove, and the relief in the cove is about 800 feet. Jamestown, the county seat of Fentress County, is the nearest town about 4 miles to the

northeast (Fig. 2). Buffalo Cove is reached from Jamestown by a graded road that connects with State highway No. 28 at a point 1.5 miles south of the town. The graded road traverses the crest of a ridge known as The Temple on the north side of the cove. Jamestown is served by the Oneida and Western Railroad which connects with the Southern Railway at Oneida, Tennessee.

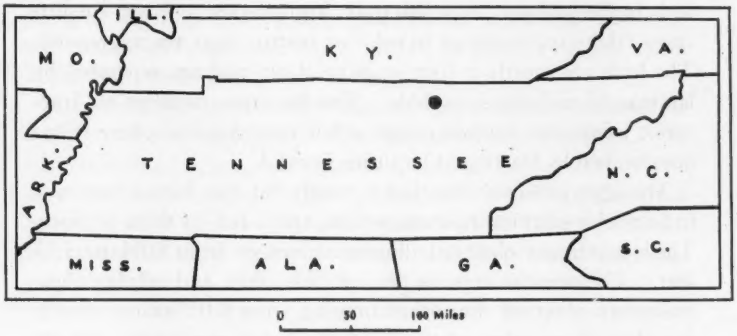

FIG. 1. Outline map showing location of the Buffalo Cove area in Tennessee.

The current interest in strontium compounds led to an examination of the better exposures of the strontium ore on July 10–12, 1942, by the writer and J. S. Williams of the Geological Survey. The cooperation of Mr. Williams, particularly in determining the stratigraphic occurrence of the celestite, is gratefully acknowledged. The time consumed in the examination would have been much longer had it not been for the helpful guidance of W. H. Whitè of the Tennessee Geological Survey, Ernest Gernt of Jamestown, and H. E. Stephens of Buffalo Cove. The Wolf River Corporation, operator of the Youngs quarry, kindly permitted an examination to be made, and the owner of the property, Mr. Joe Youngs, has permitted publication of estimated reserves. The manuscript has been read critically by W. T. Schaller, G. F. Loughlin, and G. R. Mansfield, whose helpful suggestions are acknowledged.

OCCURRENCE OF THE CELESTITE.

Physical Character of the Ore. The celestite occurs most commonly intercrystallized with pale-pink dolomite and colorless calcite in miniature orebodies that are termed aggregates in this paper. The aggregates are enclosed in beds of the Glen Dean limestone, of upper Mississippian age. The limestone of these beds is fine-grained, brownish gray, argillaceous, and non-fossiliferous; there is no change in color or texture near the aggregates. The beds are mostly a foot or more thick, and are separated by laminae of carbonaceous shale. The limestone contains no fractures, joints, nor veinlets except a few open fissures where it has been broken by blasting at localities 1 and 2.

The aggregates are spherical to nearly flat, but show a tendency to be thickly elliptical in cross section, and a few of them coalesce. Their maximum observed dimension ranges from 0.04 to 1.35 feet. The celestite crystals are colorless, thin, and tabular, their maximum observed dimension ranging from 0.05 inch to nearly 5 inches; aggregates of the smaller crystals are white or light gray. The calcite is much less abundant than celestite or dolomite; it is fine-grained, mostly finer than any of the celestite, but coarser than the calcite of the enclosing rock. The dolomite, including some magnesian calcite, is coarser grained than the calcite, but few crystals are more than 0.25 inch across.

The proportions of these minerals and the extent to which they are segregated or intermixed differ greatly in adjacent aggregates. Most of the aggregates show no zoning of the minerals, but a few consist largely of dolomite with large celestite crystals embedded in the center or extending completely through the mass. Dolomite is particularly variable in quantity. Many aggregates in the lower beds contain no visible dolomite, and these are more nearly spherical in shape than those above. In other aggregates, more common in the upper than in the lower beds, dolomite is more abundant than celestite and calcite combined; such aggregates are, in general, more irregular in shape than are those without visible dolomite. The quantity of celestite is relatively large

in aggregates without visible dolomite, averaging about 96 per cent as shown by analyses.

Internal cavities have been formed in some aggregates by the leaching of celestite and calcite during weathering. Such cavities are rather common in the uppermost beds at the Youngs quarry where the effects of weathering are evident, but no cavities were seen in aggregates in the lower beds where there is no evidence of leaching. Many aggregates in the upper beds also contain much chert regardless of the extent of weathering, but those in the lower beds do not contain chert.

Sphalerite, pyrite, and anhydrite are very scarce constituents of the unweathered aggregates. The sphalerite, found in only 7 out of hundreds of aggregates examined, occurs in irregular crystals mostly 0.1 to 1.0 inch in length. Most of it is amber-yellow, but irregular parts of some crystals appear black in hand specimens. In transmitted light the darker sphalerite is deep violet, but it apparently occurs in zones in the yellow crystals rather than in separate crystals. Pyrite is even scarcer and occurs as stringers of cubic crystals, each less than 0.05 inch across, at the contact with the limestone. This variety of pyrite appears to be genetically different from more common films of iron sulphide that occur mostly in the limestone and rarely in the mineral aggregates. Where the films cut the aggregates, they cut the enclosing limestone as well, but the stringers of cubic crystals are confined to the boundaries of the aggregates. The anhydrite occurs in microscopic crystals apparently enclosed in the celestite.

Celestite also occurs, though much less abundantly, as single crystals and groups of crystals embedded in the limestone irrespective of the occurrence of the aggregates. The crystals are similar to those in the aggregates, but are not accompanied by crystals of the other minerals. The groups of crystals commonly have a roughly spherical outline, but the crystals are oriented diversely within the groups, and there is no contact or line of separation between the group and the enclosing limestone. The limestone between the crystals of a group is identical in appearance and continuous with that immediately enclosing the group and with lime-

stone many feet distant from any known celestite crystals or celestite-bearing aggregates. For the later consideration of the origin of the aggregates, it is necessary to maintain a clear distinction between the celestite in the aggregates and that occurring free in the limestone.

TABLE 1.

ANALYSES OF STRONTIUM ORE FROM BUFFALO COVE.
J. G. Fairchild, analyst.

	Sample 1-A	Sample 1-B	Sample 5	Sample 6
		Insoluble in acid.		
SrO	54.46	45.07	53.89	34.72
CaO	0.64	——	.28	——
SO_3	42.95	34.81	42.46	26.82
BaO	None	None	None	Faint trace
SiO_2	None	None	None	None
		Soluble in acid.		
CaO	0.81	6.45	1.13	12.45
MgO	.10	3.33	.49	6.42
FeO	.05	.74	.05	.93
MnO	.02	.08	.02	.10
CO_2	.42	9.20	1.34	17.34
	99.45	99.68	99.66	98.78
		Calculated combinations.		
$SrSO_4$	96.53	79.88	95.53	61.54
$CaSO_4$	1.53	— — —	.67	——
$CaCO_3$	1.06	11.52	2.02	22.23
$MgCO_3$	.20	6.98	1.06	13.43
$FeCO_3$	.08	1.19	.10	1.50
$MnCO_3$	.03	.13	.03	.16
	99.43	99.70	99.41	98.86

Chemical Composition of the Ore. Four samples of strontium ore from different aggregates, trimmed free of limestone, were analyzed in the chemical laboratory of the Geological Survey. The analyses are shown in Table 1. The samples were collected from localities 1, 5, and 6 which are shown in Fig. 2; the exposures of the celestite zone at these localities are described be-

low. Sample 1-A represents the best grade of ore in the Youngs quarry (locality 1); it contains no visible dolomite. Sample 1-B, from the same quarry, represents ore of medium grade containing an appreciable amount of pink dolomite. Sample 5 was equivalent in appearance to sample 1-A, and sample 6 was equivalent to

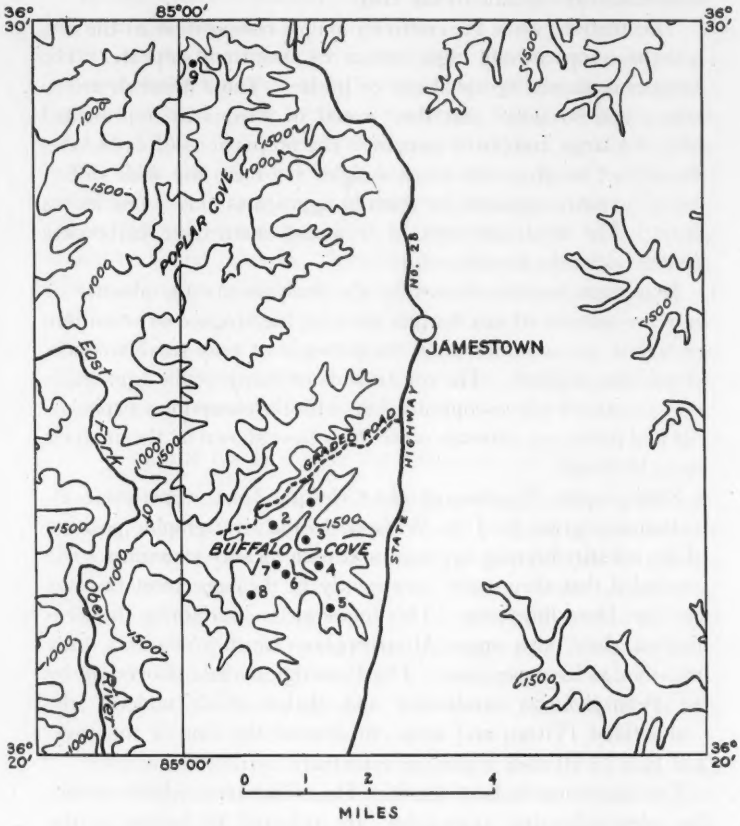

FIG. 2. Map of the Buffalo Cove area, from the Wartburg and Standingstone topographic sheets of the Geological Survey. The numbered dots represent localities described.

sample 1-B but contained more dolomite. Samples 1-A and 5, therefore, are representative of the high-grade ore in Buffalo Cove, and samples 1-B and 6 give the approximate range of medium-grade ore. Very little ore inferior to that of sample 6 was included in a trial production of concentrates that was being undertaken at the time of the visit.

The analyses show the relatively simple composition of the ore, and the comparatively high content of strontium sulphate. The samples contained no sphalerite or pyrite. These minerals are so scarce and irregular that they would be adequately represented only in a large, composite sample. The proportions of carbonates should not be given too much weight, for there are wide differences in relative amounts of them in aggregates only a few inches apart. The small amounts of iron and manganese carbonates give the dolomite its pink color.

Important features shown by the analyses are the absence or extreme scarcity of any barium mineral, the absence of strontium carbonate (strontianite), and the presence of only small amounts of calcium sulphate. The constituents of many of the aggregates were examined microscopically, but, with the exception of sphalerrite and pyrite, no minerals other than those shown by the analyses could be found.

Stratigraphic Position of the Celestite Zone. Particular attention was given by J. S. Williams to the stratigraphic position of the celestite-bearing aggregates at each locality examined. He concluded that they occur consistently in the uppermost beds of the Glen Dean limestone. This limestone is overlain by the Pennington shale, also upper Mississippian, which contains a little limestone in its upper part. The Pennington shale is overlain by the Pennsylvanian sandstones and shales which underlie the Cumberland Plateau and crop out around the rim of the cove. The beds of all these rocks are essentially horizontal.

The uppermost beds of the Glen Dean limestone, which contain the celestite-bearing aggregates, are referred to herein as the celestite zone. They crop out at an altitude of about 1,200 feet apparently around the entire cove. As described below, the

celestite zone is fully exposed at only two of the localities shown in Fig. 2; it has a thickness of 10.9 feet at one of these, and of 7 feet at the other. A minimum thickness of 20 feet is apparent at a third locality, but it could not be determined whether all of the beds at this locality contain celestite.

It was inferred that the upper part of the Glen Dean limestone might constitute a celestite zone over a very large area. In order to test this inference, a favorable locality was selected at random from the map, and the upper part of the limestone was examined there. The locality (number 9, Fig. 2) is at the north end of Poplar Cove, seven miles north of Buffalo Cove. The upper beds of the Glen Dean here contain generally ellipsoidal bodies similar in appearance to many of the aggregates of Buffalo Cove, but only dolomite, calcite, glassy quartz, and a little pyrite could be found in them. Insoluble residues contain no celestite. Time was not available to examine other localities outside of Buffalo Cove, but Martin,[2] who has described the lithologic character and insoluble residue of the Glen Dean limestone in Western Kentucky, reports neither celestite nor mineral aggregates similar in form to those described herein.

ORIGIN OF THE CELESTITE-BEARING AGGREGATES.

General Considerations. The unusual composition of the mineral aggregates and the lack of any direct evidence of a process by which the minerals accumulated make it very difficult to reach a conclusion regarding their origin. The apparent absence of jasperoid, fluorite, and barium, lead, copper, and arsenic minerals also makes it difficult to correlate the aggregates with the characteristic ores of the Mississippi Valley region or with those of the Appalachian Valley region. The mutual relations of the few minerals present shed little light on the problem.

Robinson[3] briefly describes the occurrence of celestite with barite in the veins of Central Kentucky, and states also that micro-

[2] Martin, H. G.: The insoluble residues of some Mississippian limestones of Western Kentucky. Kentucky Geol. Surv., Ser. 6, 41: 168, 1931.

[3] Robinson, L. C.: The vein deposits of Central Kentucky. Kentucky Geol. Surv., Ser. 6, 41: 28, 33, 76, 98, 1931.

scopic celestite crystals are disseminated in the [adjacent?] limestones and shales. The occurrence of celestite elsewhere, as summarized by Clarke [4] and Moore,[5] includes limestone and saline environments that indicate sedimentary chemical deposition, pyroclastic environments that suggest solfataric origin, and mineral deposits of undoubted hydrothermal origin.

There is reasonably good evidence that the celestite-bearing aggregates in Buffalo Cove were formed in the limestone after the limestone had become consolidated. The weight of the larger aggregates, owing to celestite's specific gravity (3.96), would have caused rapid settling with distortion of the shaly bedding laminae had they been formed in the original calcareous mud. The same would have been true if the strontium had been present originally as strontianite, for this mineral has a specific gravity of 3.7. A very few of the aggregates contain angular fragments of limestone identical with that which encloses the aggregates. The limestone, therefore, must have been sufficiently solidified to become fragmented before the fragments were enclosed in the celestite-carbonate matrix. The lack of concentric zoning in the aggregates makes it also unlikely that they developed as concretions after the limestone was solidified.

There is no evidence, on the other hand, that the isolated celestite crystals and groups of crystals disseminated in the limestone were formed after the limestone had consolidated. In view of the occurrence of syngenetic or diagenetic celestite elsewhere disseminated in limestones and saline deposits, it would seem unnecessary to postulate an epigenetic origin for these crystals. It is more likely that they were formed by the precipitation of strontium sulphate from connate water during the process of consolidation. As the mineral aggregates, including the celestite in them, were clearly formed after the limestone consolidated, it remains to account for the minerals that constitute the aggregates.

[4] Clarke, F. W.: The data of geochemistry. U. S. Geol. Surv. Bull. 770: 224, 248, 589, 1924.

[5] Moore, B. N.: Strontium minerals, in Industrial Rocks and Minerals. A. I. M. E., New York, 1937. Pp. 838–841.

This problem involves consideration of, first, the possible sources of the minerals, and, second, the possible mode of emplacement.

Sources of the Minerals. Of the three principal minerals in the aggregates, celestite and calcite have obvious sources in the enclosing limestone. These minerals could have been concentrated by ground water, and the greater solubility of celestite[6] would account for the proportionately high content of celestite in the aggregates. The lack of bleached zones and textural differences in the limestone adjacent to the aggregates, however, indicates that celestite and calcite were not derived by radial leaching; a possible method by which they were derived is discussed below.

The source of the third principal mineral, dolomite, is not apparent. There is no dolomitic limestone above the Glen Dean, and it is most unlikely that any was present in the Pennsylvanian rocks that have been removed by erosion. The Glen Dean limestone effervesces violently with dilute acid; it obviously contains very little dolomite, and there is no evidence that enough of it has been dissolved at any time to furnish the large amount of dolomite in the ore. Dolomite, furthermore, has a lower solubility than celestite or calcite, yet it is much more abundant than calcite in most of the aggregates, and is nearly as abundant as celestite in many. The dolomite must have come from below the Glen Dean, and the writer is inclined to correlate it with the vein-forming dolomite known in both the Mississippi Valley and Appalachian Valley regions.

The minor minerals, sphalerite, anhydrite, and pyrite, are present in such small amounts that they have little diagnostic value. All are known elsewhere to be formed by supergene processes, and sphalerite and pyrite also occur elsewhere in hypogene mineral deposits. Here all of the anhydrite apparently is enclosed in the celestite, and appears to have been formed by reaction between available calcium carbonate and sulphate water as the celestite crystallized. Sphalerite and pyrite, however, required the addition of at least zinc and iron even if organic matter in the limestone furnished the sulphur. As all of the sphalerite seen occurs

[6] Clarke, F. W.: op. cit., p. 589.

with dolomite and in relatively large crystals, it is possible, but by no means certain, that the source of the sphalerite was below the Glen Dean limestone, and that it was deposited with the dolomite. The pyrite could have been derived from the leaching of rocks above the Glen Dean limestone, but the contrast between its cubic form and the fern-like form of iron-sulphide films undoubtedly deposited by groundwater makes it more likely that the cubic pyrite was introduced with the dolomite and sphalerite.

To summarize, the celestite, calcite, and anhydrite were probably derived from the Glen Dean limestone. The dolomite almost certainly was not derived from this limestone, and, if not, could have come only from depth. The sphalerite and pyrite were probably introduced with the dolomite.

Emplacement of the Minerals. If the celestite-bearing aggregates were formed after the Glen Dean limestone consolidated, it would appear that they were formed also after the overlying Pennington shale was deposited. The beds of the two formations are conformable, and the Glen Dean beds grade upward into the shales by a marked decrease in calcium carbonate in a vertical interval of a few feet. The aggregates occur immediately below the transition beds. Those in the upper part of the celestite zone are, in general, more irregular in shape than those in the lower part; the common presence of chert and the greater amounts of dolomite in aggregates in the upper part of the zone have been noted above. Aggregates that coalesce are scarce, but are relatively more abundant in the upper than in the lower part of the zone. They are not nearly abundant enough, however, to indicate a typically hydrothermal replacement origin for the ore. It seems, rather, that the positions of the aggregates were determined prior to the deposition of the ore.

The total lack of brecciation and veining shows conclusively that openings for mineral deposition were not formed mechanically. The rare fragments of limestone isolated in a few of the aggregates must have been dislocated by solution, for the limestone surrounding such bodies is not fractured. Bassler[7] states that

[7] Bassler, R. S.: The stratigraphy of the Central Basin of Tennessee. Tenn. Div. Geol., Bull. 38: 161, 1932.

there is an unconformity at the top of the Pennington shale involving the absence of possibly as much as 8,000 feet of rocks present elsewhere. This information suggests a clue to the origin of the openings in which the minerals were deposited. If the unconformity is erosional, meteoric waters could have penetrated the Pennington shale, which is only about 200 feet thick in the Buffalo Cove area. The water would have been barred from further downward migration by the dense, unfractured Glen Dean limestone, and could have formed solution cavities in its upper beds, which now constitute the celestite zone. The process of solution would have been most active in the topmost beds of the zone affected, forming in them more irregular and more commonly coalescing cavities than those in the lower part of the zone. Solution channels between the aggregates, although relatively large in the upper beds, would have been smaller, perhaps even microscopic, in the lower beds. The chert, if deposited by the meteoric water, also would have become localized in the topmost beds of the zone as the water passed from a shale to a limestone environment. These possibilities accord with the shapes of the aggregates and the occurrence of chert in the zone.

Celestite, having the greater solubility, would have been dissolved from the walls of the cavities in proportionately greater amounts than calcite; therefore, limestone containing celestite in greatest relative abundance would have been most susceptible to solution, and hence the form of many of the cavities would approximate the spherical to lenticular shape of the groups of original celestite crystals in the rock. As the water became saturated with the dissolved substances, precipitation of calcium carbonate and strontium sulphate would have occurred in the cavities, perhaps largely sealing any connecting passages of microscopic dimensions. There is no evidence to indicate whether the cavities were completely filled, but the selection of the same loci for the deposition of dolomite suggests that they were only partly filled at the time the dolomite was introduced.

The lack of a source for the dolomite in or above the Glen Dean limestone and the probability that the dolomite was introduced

from depth have been discussed. It is inferred that the dolomite, and probably with it the sphalerite and pyrite, were introduced into the Glen Dean limestone by post-Mississippian hydrothermal solutions along fissures such as those in which the vein deposits of dolomite, barite, celestite, sphalerite, galena, pyrite, fluorite, and other minerals were deposited in various combinations in the surrounding region. No such vein was seen in the few exposures examined in Buffalo Cove, but coarsely crystalline dolomite occurs widely as a vein mineral associated with ore deposits believed to be of hydrothermal origin in both the Mississippi Valley [8] and the Appalachian Valley [9] regions.

It is recognized that hydrothermal solutions may derive carbonates from wall rocks through which they move, and that the carbonates may be transferred for very small or great distances. The depth of the Beekmantown and older dolomites below the top of the Glen Dean limestone at Buffalo Cove is unknown, but is probably about 2,000 feet; highly magnesian limestones are unknown in the intervening section. It appears, therefore, that the constituents of the dolomite in the aggregates were transferred at least this distance by solutions that rose along fissures and were dammed by the overlying Pennington shale, spreading laterally through the cavities in the uppermost beds of the Glen Dean limestone. The spreading could have extended long distances from a few widely spaced fissures. It is not likely that the hydrothermal solution was of high temperature, and, if it mingled with the meteoric water supposedly still present in the cavities, the temperature would have been lowered sufficiently to cause direct deposition of the dolomite and sulphides without reaction with the limestone in the walls of the cavities. The invading solution was evidently under too little pressure to be forced through the relatively impervious limestone, or to pass freely along the more

[8] Bastin, E. S. and others: Contributions to a knowledge of the lead and zinc deposits of the Mississippi Valley region. G. S. A. Spec. Pap. 24: 106, 1939.

[9] Currier, L. W.: Zinc and lead region of southwestern Virginia. Virginia Geol. Surv. Bull. 43: 78, 1935; Kesler, T. L.: Sienna ("ocher") deposits of the Cartersville district, Georgia. ECON. GEOL. 34: 334–335, 1939.

minute connecting channels that had been largely sealed by celestite and calcite.

This possible origin for the mineral aggregates is offered without firm conviction. It is merely the result of an attempt to harmonize features that are puzzling and in large part contradictory. The occurrence of the celestite in Buffalo Cove has little in common with that of the barite in the Appalachian Valley region, and the origin of the celestite-bearing aggregates undoubtedly is more complex than that of the barite ores.

EXPOSURES OF THE CELESTITE ZONE EXAMINED.

The Youngs Quarry. The Youngs quarry (locality 1, Fig. 2) provided the only exposure in the cove that was adequate for an estimate of celestite reserves in any part of the zone. As shown in Fig. 3, the quarry has been opened in an outcrop of the upper Glen Dean beds on a narrow divide between ravines which drain southward into Buffalo Cove Creek. Numerous small openings have been made nearby, and those that best exposed the celestite ore are shown as prospects in Fig. 3.

The southeast end of the quarry face exposes the entire thickness of the celestite zone, which here is 10.9 feet, for a distance of 33 feet. The upper part of the zone, 6.5 feet thick, contains weathered, chert-bearing aggregates from which most of the celestite and much of the carbonates have been leached. Such aggregates do not constitute strontium ore. The lower 4.4 feet of the zone contains aggregates that are mostly fresh, sound, and chert-free. Such aggregates are regarded as possible strontium ore.

The quarry and adjacent prospect openings indicated that at least the lower part of the celestite zone probably contains aggregates of the same general grade and abundance for some distance into the ridge to the north, but it is not likely that underground quarrying could be carried on economically because of the low strength of the overlying Pennington shale. It was assumed, therefore, that quarrying might be practicable only as an open-cut operation. By connecting the quarry and the principal pros-

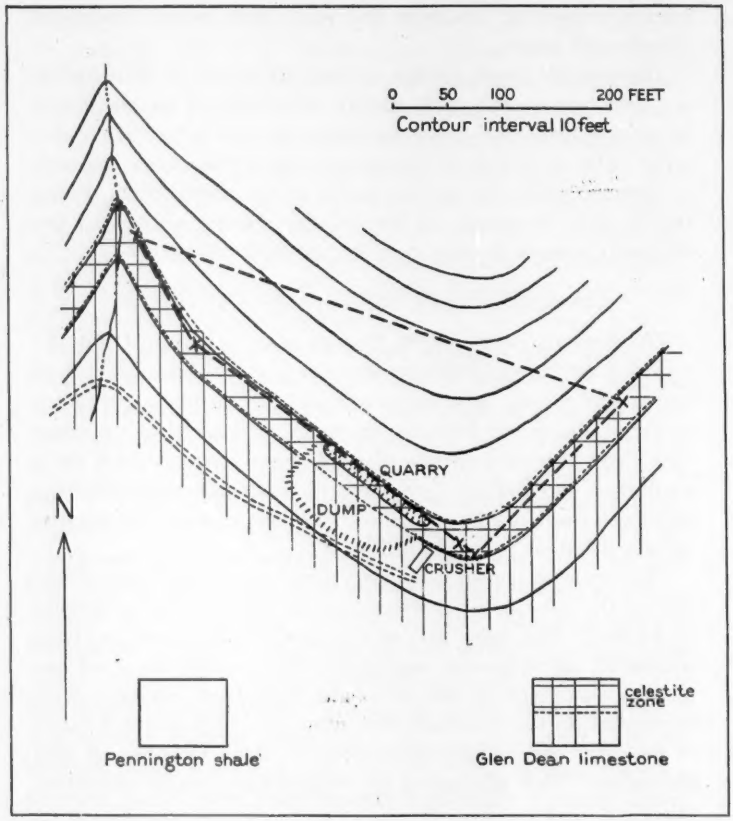

FIG. 3. Sketch map of the Youngs quarry and vicinity, showing geologic occurrence of the ore-bearing beds, and outline of ore block computed.

pect openings on each side of the divide, a reasonably indicated quadrilateral block was outlined whose general grade is exposed on three sides. This block is shown by the heavy dashed lines in Fig. 3. The thickness of the shale overburden ranges from

zero on the three sides prospected to a maximum of 30 feet on the north side of the block opposite the quarry.

To determine the approximate amount of celestite in the block, the vertical face of the lower 4.4 feet of the ore zone, where fully exposed for 33 feet in the quarry, was examined in detail. This part of the zone contained 177 celestite-bearing aggregates, each of which was measured and computed as an ellipse. The proportion of the combined area of the aggregates to the total area of the face was then computed, and was used to represent the volumetric proportion of strontium ore to total material in the block.

TABLE 2.

STATISTICAL RESULTS OF THE EXAMINATION OF THE YOUNGS QUARRY AND ADJACENT OPENINGS.

Face of lower part of celestite zone in the quarry.		
1. Area (33 ft. × 4.4 ft.)	145.2	square feet
2. Combined area of 177 aggregates in the face	8.6180	square feet
3. Combined area of cavities in 10 of the aggregates (estimated)	0.1189	square feet
4. Net area of strontium ore in the face	8.4991	square feet
5. Proportion of net area of ore to area of face (from items 4 and 1)	5.85	per cent
6. Proportion of area of celestite to net area of ore (estimated average)	70	per cent
Block of lower part of celestite zone adjacent to the quarry.		
7. Surface area	96,449	square feet
8. Volume (total)	424,374	cubic feet
9. Volume of limestone, exclusive of ore	399,548	cubic feet
10. Volume of ore in the limestone (based on item 5)	24,826	cubic feet
11. Volume of celestite in the ore (based on item 6)	17,378	cubic feet
12. Weight (total)	36,496	short tons
13. Weight of limestone, exclusive of ore	33,674	short tons
14. Weight of ore in the limestone	2,822	short tons
15. Weight of celestite in the ore	2,148	short tons
16. Proportion of weight of ore to total weight of block	7.73	per cent
17. Proportion of weight of celestite to total weight of ore	76.12	per cent
18. Proportion of weight of celestite to total weight of block	5.89	per cent

The proportionate areas of celestite and carbonates exposed in aggregates of different grades were estimated, and later were checked roughly by solubility tests with hydrochloric acid. From this an approximate average proportion of the area of celestite to the total area of the aggregates in the face was derived, and was used to represent the volumetric proportion of celestite to strontium ore in the block.

The volume data thus obtained were then applied to the calculation of weights by use of the following specific gravities: celestite 3.96, dolomite 2.87, and argillaceous limestone 2.7 (assumed). Calcite is present in relatively small amounts, and is so similar in appearance to the finer-grained celestite that it could not be computed separately. It was included with the dolomite on the basis of the solubility tests. The results of the measurements, estimates, and computations are shown in Table 2. The proportion of celestite in the ore (item 17) is lower than the average proportion of strontium sulphate in the four analyses given above owing to the fact that two of the four samples analyzed were of high grade. It could not be assumed that fifty per cent of the ore in the block would be of this grade.

Other Exposures. Other localities at which exposures of the celestite zone were seen are indicated by numbers 2 to 8 in Fig. 2. The celestite-bearing aggregates at locality 2, which has been prospected, are of decidedly lower grade than those at the Youngs quarry. The aggregates at locality 8, which has not been prospected, consist largely of fine-grained calcite with very small amounts of quartz and pyrite. Celestite could be found only microscopically in an insoluble residue. Localities 2 and 8, therefore, may establish the western limit of celestite of any economic importance.

There are two exposures of the limestone containing aggregates of strontium ore in the shallow channel of a ravine at locality 3. One exposure is 13 feet stratigraphically above the other, but the beds between are covered by soil and boulders. The overall thickness of the section from the lowest outcrop to the highest is 20 feet, but the full thickness of the zone could not be measured here. Most of the aggregates seen appear to be equal in grade to the better aggregates at the Youngs quarry.

The proportion of celestite in the aggregates at localities 4, 5, 6, and 7 is approximately the same as that at the quarry. The celestite zone is fully exposed at the level of an intermittent stream at locality 5, where it is 7 feet thick, but the aggregates are not

quite so abundant as they are at the quarry. The beds of the celestite zone are so poorly exposed at localities 4, 6, and 7 that no conclusions could be reached regarding their thickness. The celestite-bearing aggregates, however, appear to be about as abundant in the limestone as are those at the Youngs quarry.

POSSIBILITY OF LARGE-SCALE PRODUCTION OF CELESTITE.

The richer aggregates of strontium ore in the Glen Dean limestone are apparently limited to the central and eastern parts of Buffalo Cove. The slopes of the cove are scalloped by many ravines, and the upper part of the Glen Dean limestone on each divide between the ravines is a potential quarry site.

Parts of the celestite zone, at localities, 3, 4, 6, and 7, appeared in only a brief examination to be roughly equivalent to the block computed at the Youngs quarry. There is good reason, therefore, to believe that a dozen or more favorable sites could be located in a short time with a rather small amount of trenching and blasting to determine the thickness and general grade of the celestite zone.

The absence of barite in the strontium ore and the scarcity of other impurities of high specific gravity greatly simplify the treatment that would be necessary to make an unusually pure celestite concentrate.

As there apparently is no established price for exceptionally pure celestite concentrates, the future demand for strontium salts will determine whether or not material of the grade shown in the analyses and in Table 2 can be quarried and concentrated economically from fresh limestone. For commercial purposes, it may be estimated that the limestone and ore combined, in the lower part of the celestite zone, has a value per ton in place about one-twentieth of that offered per ton for the concentrates.

If there were a demand for a steady output of concentrates, the inaccessibility of the cove, particularly during wet weather, would make it necessary to construct a mill in Buffalo Cove. The mill could handle the feed from a number of quarries, making it

necessary to transport only concentrates to the level of the Cumberland Plateau. A cable car at the east end of the cove, near State highway No. 28, probably would be more economical for this purpose than would trucks which have access only near the west end.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.
July 28, 1943.

SOME ENGINEERING ASPECTS OF RIVER SAND DEPOSITS.

D. P. KRYNINE.

ABSTRACT.

In general the coarseness of sand may be determined by different methods in which size distribution (cumulative) curves are used. To obtain such curves, an elaborate mechanical analysis of the sand material is needed. It is shown in this article how the coarseness of sand at different sections of a river may be quickly, though approximately, defined by a single numerical value, without recourse to cumulative curves. Illustrated is a particular case of the bed of the Thames River, in New London, Conn. Some field observations on the compactness of river sand deposits are included in the article.

SPECIFICATIONS for earth dams, dikes and other kinds of embankments generally require a certain size distribution (coarseness) of the borrow pit material. Specifically, for dikes and other embankments parallel or close to a river, the sand material extracted from the river itself is used, at least in part. It is important, therefore, to know in advance in a quick, though approximate, way the coarseness of the sand material at different sections of the river. There are various systems of classification of sands as used by geologists and by engineers. In either case a size-distributions (cumulative) curve has to be constructed for each sample. Geologists take advantage of this curve applying variations of different statistical methods [1] whereas engineers generally use the classification as proposed by Allen Hazen.[2] For instance, in the Parker D. Trask method quartile and median diameters are determined using the size distribution (cumulative) curve. In the Allen Hazen method, the diameters of particles, finer than 60 per cent and 10 per cent of the bulk of the sample by dry weight,

[1] Krumbein, W. C.: Graphic presentation and statistical analysis of sedimentary data. "Recent Marine Sediments." A. A. P. G., 1939. Pp. 558–591.

[2] Krynine, D. P.: Soil Mechanics, New York, 1941. P. 21.

are determined; to use this method also a size-distribution curve is needed. The ratio of both diameters referred to is the "coefficient of uniformity," whereas the smallest of these two diameters is the "effective size" of the sample. The disadvantages of the methods in question for a quick and rough work in which generally only three sieves (Nos. 10, 40 and 200 or 270) are used for the mechanical analysis, are obvious: (*a*) a size distribution curve is to be constructed for each sample; and if there are several different sands in a boring, a corresponding number of size-distribution curves are needed per boring; (*b*) a size distribution curve cannot be constructed accurately from three points given by three sieves only. In the first part of this article a simple method of characterizing the coarseness of a given sand (or of a group of sands in a boring) by a single value is given. This method resembles somewhat that used by geologists for characterizing the roundness of a sand[3] or by engineers in concrete work[4] (the "fineness modulus method"). In the second part of this article some ideas on the compactness of river sand deposits as obtained from simple observations on engineering projects are advanced.

I. COARSENESS OF SAND.

Figure 1 represents the cross section of the Thames River in New London, Connecticut. This is a tidal part of the river. The granite rock in the channel and on the shores is covered with sand; above the sand there is an overburden of organic silt (black mud) in the river and some loam on the shores. Numerical data corresponding to each of the river borings 8, 9, 10, and 11 (but not 11a and 11b) in the figure are averages of four borings located in each case at the corners of a rectangle 100 ft. × 50 ft.

[3] Russell, R. D. and Taylor, R. E.: Roundness and shape of Mississippi river sands. Jour. Geol. 45: 225–267, 1937.

Krumbein, W. C.: Measurement and geological significance of shape and roundness of sedimentary particles. Jour. Sed. Petr. 11: 64–72, 1941.

[4] Moore, H. F.: Textbook of the Materials of Engineering. New York, 1936. P. 263.

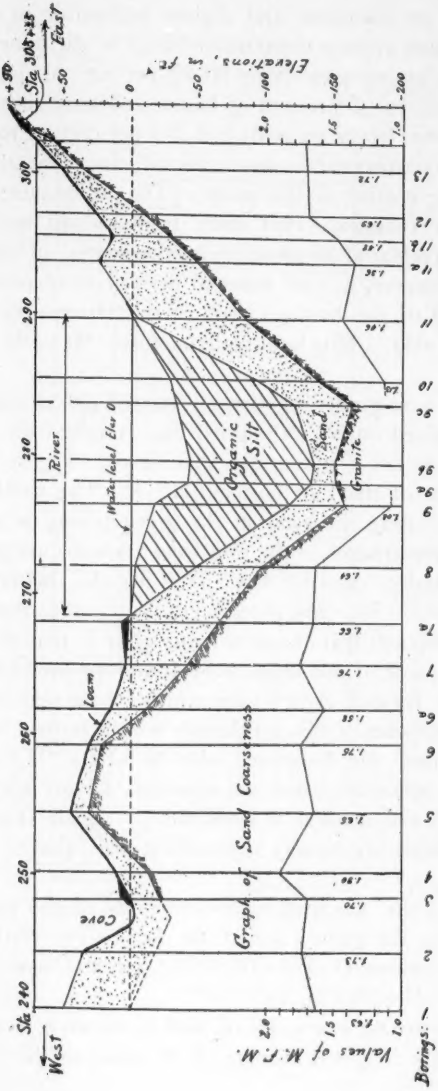

FIG. 1. Cross Section of the Thames River, New London, Conn.

The sands are micaceous and slightly feldspathic in composition. Estimated average composition based on the mineralogical analysis of a few samples shows 80–85 per cent of quartz, 5–8 per cent of feldspar, 5 per cent of biotite and some muscovite, 5 per cent of other heavy minerals and 2–3 per cent of rock fragments. The quartz occurs in two main varieties: clear, or colored with persisting coating of iron oxide. The provenance of sands appears to be complex. Part came from an old sedimentary cover either preglacial or more likely interglacial in age. The main bulk, however, is local material derived from post or late glacial erosion of the drainage basin of the Thames River itself (bedrock and till). This local material forms 90 to 95 per cent of the sands.

The sands were graded as coarse (retained on No. 10 sieve), medium (retained on No. 40 sieve), fine (retained on No. 200 sieve) and very fine (passing No. 200 sieve). Figure 2 shows the log of one of the four borings, No. 8. The width of the column representing the sand in the given boring is one (see Fig. 2), and percentages of the four sand fractions are plotted as fractions of unity. In each layer (for instance, between Elev. — 48 and Elev. — 54) these percentages expressed as fractions of unity are multiplied: that of coarse material by 3; that of medium material by 2; that of fine material by 1, and the products added. This furnishes for each layer a value which for the sake of brevity and for the purposes of this article only will be termed "modified fineness modulus" and designated with the letters "M.F.M." If all sand were perfectly coarse, the value of M.F.M. would be 3; for a perfectly fine material it would be 1. Again, if in a sand all four fractions are equally represented, the value of M.F.M. would be 1.5.

The value of the "modified fineness modulus" is also the sum of distances from the right edge of the log to the vertical lines separating fractions (OA + OB + OC, for the layer between Elev. — 48 and — 54, Fig. 2).

To characterize the coarseness of sand in the whole boring by a single value, the weighted average of all values of the "modified

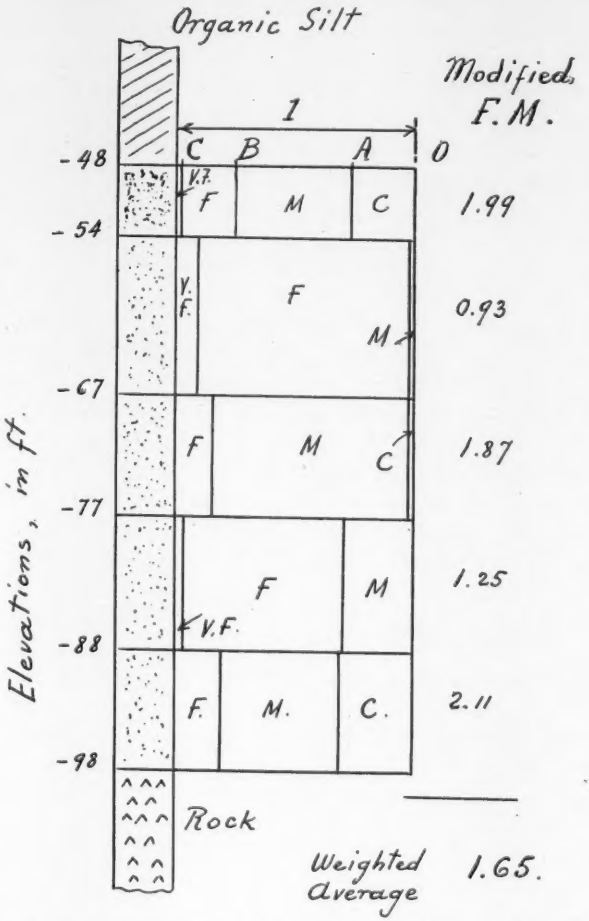

FIG. 2. Log of a Boring, Showing Variable Coarseness of the Sand in the River.

fineness modulus" in different layers should be computed. This can be done by multiplying the value of M.F.M. of each layer by the thickness of the latter, by adding these products and by dividing the sum by the total thickness of the sand deposit in the given boring (50 ft. in Fig. 2).

The values of M.F.M. are plotted at the bottom, Figure 1. These values in the given case range between 1 and 2. A simple visual inspection of this graph shows that the sand on the western (right) shore of the Thames River in New London is coarser than on the opposite shore, and that the sand in the river itself is finer than on the banks. The graph in question approximately follows the configuration of the rock channel, which means that the sand at the middle of the river is the finest. The depression of the graph at boring 11-a (Fig. 1, bottom) corresponds to an accumulation of fine sand at that place as revealed by the corresponding bulge in the longitudinal profile (Fig. 1, top).

The weighted average M.F.M. may be computed for the whole profile as in Figure 1 or for any particular portion of it. This can be done by multiplying each of the values of M.F.M. shown on the graph referred to as belonging to the given portion by half of the sum of the distances to the neighboring values, by adding the products and by dividing the sum by the width of the portion considered. Such computations permit comparing the coarseness of sand in different sections of the same river; or in different rivers; and generally in any two or more sand deposits.

It should be clearly understood that the results obtained by the method proposed can be generalized only if a sufficiently large number of analogous items (similar rivers or similar sand deposits) have been studied. Furthermore, these results are qualitative rather than quantitative because, after all, the value of the modified fineness modulus as described, is a conventional one.

II. COMPACTNESS OF SAND.

Very few, if any, river sand deposits are uniform and homogenous. In the opinion of the writer, among the many causes which contribute to the nonuniformness of sand strata, are boulders. To check this opinion, pile driving records were studied.

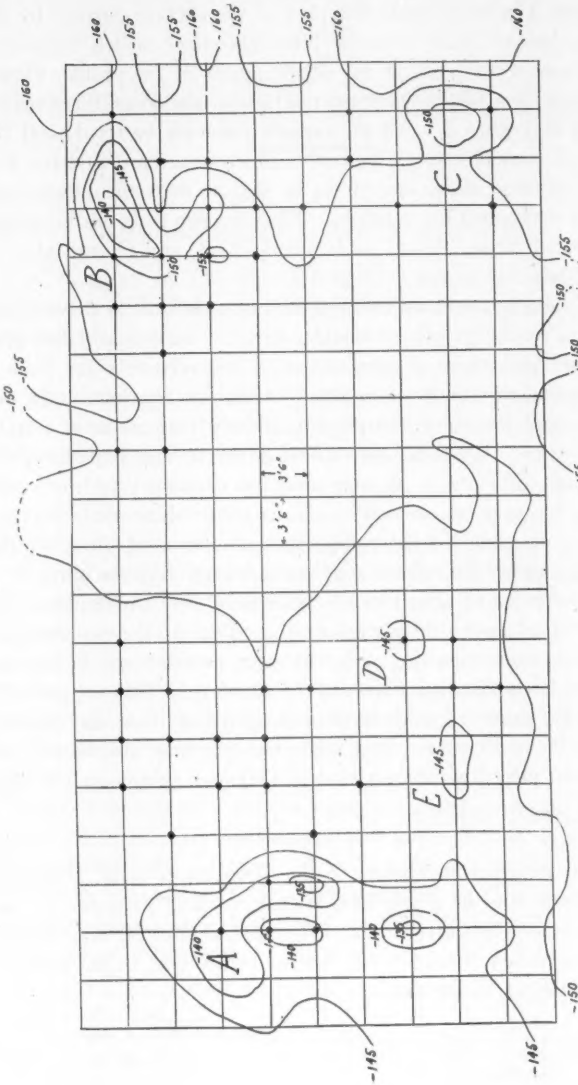

FIG. 3. Plan of a Bridge Pier Showing Relative Difficulty of Driving Piles.

Figure 3 is the contour line plan of the surface formed by the bottom tips of heavy metallic piles (H-piles) which support a bridge pier constructed at one of the points of the profile, Figure 1. There is a pile at each intersection of the lines forming the pattern in Figure 3. All the outside piles are battered, and the inside piles are plumb. Those piles which were hard to drive, *i.e.*, which required more energy to be driven than the others, are marked with small black circles. They happen to be in the neighborhood of large "floats" or boulders A, B, and C, and also of smaller boulders D and E (Fig. 3).

It is rather easy to understand why it is difficult to drive a pile which is reaching rock or boulder directly underneath that pile. When the pile which is being driven is still relatively far from a rigid boundary (rock or boulder) both the frictional skin resistance and the point resistance gradually increase at a certain rate or rates. When the pile comes closer to that boundary, the increasing difficulty in driving may be explained by the rapid increase in the point resistance. In its turn, this increase is probably due to considerable compaction of the sand close to the boundary and to the reflection of stress waves from the latter.

The behavior of piles located not exactly over the boulder, but close to it, is more difficult to explain. One of the explanations is probably the compacting action of water pressure which through centuries has pushed sand toward the boulders. This is especially true if the group of piles is located upstream from the boulder (letter "B" in Fig. 3). In a tidal zone this may also be true of a group of piles downstream from the boulder (letter "A" in Fig. 3).

ACKNOWLEDGMENTS.

The writer extends thanks to the Connecticut State Highway Department for the permission to use its field records for the preparation of this article and to Professor Paul D. Krynine of the Pennsylvania State College for his helpfulness in the mineralogical analysis of the sands.

YALE UNIVERSITY,
NEW HAVEN, CONNECTICUT,
November 10, 1943.

DISCUSSION AND COMMUNICATIONS

VARIATIONS IN CHEMICAL COMPOSITION OF LOS ANGELES BASIN GROUND WATERS.[1]

Sir: A paper by Dr. Roy R. Morse discussing variations in composition of Los Angeles Basin ground waters appeared in the September–October issue of ECONOMIC GEOLOGY.[2]

This paper is of great interest locally because since 1940 the Geological Survey has been engaged in cooperative investigations of ground water in the southern part of the Los Angeles Basin. Three main objectives of these investigations are: (1) to ascertain the form, character, and watertightness of the Newport-Inglewood structural zone, the so-called coastal "barrier"; (2) to determine the lateral extent of salt-water contamination, which occurs currently along the southern and western coastal-plain margins; and (3) to discriminate the source or sources of that contamination. As one step toward these objectives, the Geological Survey has undertaken a program of intensive chemical studies directed toward discrimination of types into which the native ground waters of the area can be divided, and toward analysis of modifications that have occurred in these waters through mixture with contaminants.

Many hundreds of complete chemical analyses of the ground waters of the area were made available to the Survey at the start of its investigation. However, for the wells so sampled, the areal distribution was not uniform or complete and the depth range was irregular; not all these deficiencies could be filled within the scope of the current investigation.

[1] Published by permission of the Director, Geological Survey, United States Department of the Interior.

[2] Morse, Roy R.: The nature and significance of certain variations in composition of Los Angeles Basin ground waters. ECON. GEOL., 38: 475–511, 1943.

In the last month, Dr. Morse and the Shell Oil Company have most kindly made available to the Geological Survey some 400 complete chemical analyses of water samples taken within the period from April 1925 to February 1926 from water wells on the coastal plain; these same samples afforded the principal factual data used by Dr. Morse in his study of the variations in composition of Los Angeles Basin ground waters. The analytical data from these samples greatly extend the geographic coverage and depth range of the analyses previously available to the Geological Survey. The use of these data is acknowledged with appreciation.

In his paper, Dr. Morse defines several types of ground water of meteoric origin. The conclusions we have reached to date with respect to water types are in general agreement with his classification. However, he discusses a "marginal runoff strain" (see page 484) encountered locally in the La Habra and Irvine areas, which contains total solids about double those in the ground waters native to the Santa Ana cone and which has persistent secondary salinity. He suggests that "these samples reflect the contribution of materials picked up by the local runoff, where subsurface conditions are locally unfavorable for rapid merging with the general artesian circulation." The writer believes it unlikely that the dissolved solids picked up by the local runoff in its contact with outcrops of pre-Pleistocene strata would be sufficient to cause such an increase in total solids. For example, Santiago Creek drains a large area on the southwest side of the Santa Ana Mountains and the chemical quality of the runoff from this drainage area should be representative of the runoff that contributes to the ground water supply in the Irvine area. Complete analyses are available [3] for five samples of stream flow collected from Santiago Creek about 5 miles downstream from Santiago Reservoir in the period between October 1918 and May 1932. For these samples, the total solids range from 381 to 612

[3] Anon.: South Coastal Basin investigation, detailed analyses showing quality of irrigation waters. California Dept. Pub. Works, Div. Water Res., Bull. 40–A: 116, 1933.

and the mean is 520 parts per million. On the other hand, Dr. Morse has tabulated an average for 41 typical samples for his "marginal runoff strain," from the La Habra and Irvine areas (see p. 490). The computed average of total solids for these 41 typical samples is 865 parts per million. Thus the total solids for water samples from wells are considerably higher than for the water of Santiago Creek. With respect to the Irvine area, an alternative explanation is offered, as follows: Rocks of Cretaceous and Tertiary age crop out in considerable thickness on the west flank of the Santa Ana Mountains, and dip generally southwestward under the alluvial deposits of the Irvine area. It is believed that slow circulation of ground water through these slightly permeable older rocks is transmitting a connate component into the Pleistocene and late Tertiary water-bearing strata tapped by the water wells. In general, the deeper wells in the northeastern part of the Irvine area have the greatest content of dissolved solids. This would not be expected as a direct result of recharge by local runoff with high total solids; rather, it substantiates the postulation that connate water is a prime contributory source of the excess solids. The average secondary salinity for the water samples from Santiago Creek corresponds closely with that of the 41 samples tabulated by Dr. Morse. This would suggest that if gain of a connate component from older rocks is the cause of increase in dissolved solids, the secondary salinity of the ground water is not modified appreciably by such mixture.

In his discussion of base-exchange phenomena, Dr. Morse presents an interesting and reasonable explanation of geologic conditions and chemical reactions that produce the striking increase in the alkali/alkaline earth ratios, so well exemplified in the waters produced from many of the municipal wells of the city of Long Beach. However, he did not consider the possibility that carbonaceous deposits, which are locally abundant, are a probable cause of base exchange. Because the naturally softened waters are almost universally darkened by organic coloring matter, it is believed that the carbonaceous deposits should be considered one of the most likely base-exchange media. Carbonaceous materials

are now being used commercially to produce similar reactions involving cation transfer.[4]

Some minor alternative interpretations have been made here; they do not alter the general conclusion that Dr. Morse has presented an excellent paper, thoughtfully prepared from a wide knowledge of the general geology and geochemistry. To my knowledge, this is the first comprehensive paper on the chemical character and classification of the ground waters of the coastal-plain area in Los Angeles and Orange Counties.

JOSEPH F. POLAND.

U. S. GEOLOGICAL SURVEY,
LONG BEACH, CALIFORNIA,
April 24, 1944.

[4] Tiger, L. H.: Carbonaceous zeolites—an advance in boiler feed water conditioning. Am. Soc. Met. Eng. Trans. pp. 315–325, May 1938.

REVIEWS*

The History of Miners' Diseases, A Medical and Social Interpretation. By GEORGE ROSEN. Pp. xii + 490; Figs. 19. Schuman's (20 E. 70 St.), New York, 1943. Price, $8.50.

Mining, the "first industry to develop along capitalistic lines," is the oldest and most important with evidences of its operations remaining from earliest historical times. Since an industrial civilization is impossible without mining and metallurgy, the mineral industry defers only to agriculture in importance. It is definitely more hazardous and has always been so over its continuous history of thousands of years. Thus, the changing hazards and diseases of mining provide the best material for any history of occupational diseases.

Henry Sigerist in his introduction to Dr. Rosen's book says that "the history of occupational diseases is infinitely more than medical history. . . . Whether any use was made of medical knowledge did not depend so much on the physicians as on the social organization under which the laborer performed his work. The history of occupational diseases, therefore, reflects as in a mirror the history of industry and of labor, in other words some of the most important chapters in the history of human civilization. It not only illustrates most dramatically the development of the Industrial Revolution but the accompanying medical and social reforms."

The author traces in considerable detail actual mining methods, the conditions of mining, the developing recognition of special diseases and changing social status of the miner from Neolithic times to the end of the 19th century, or the beginning of the second Industrial Revolution.

Egyptian inscriptions referring to the turquois mines of the Sinai peninsula contain the name of the chief medical officer, and the earliest *medical* reference to a miner is found in Hippocrates' 4th Book of Epidemics, but there are no records prior to the Greco-Roman period that allow even partial reconstruction of the diseases peculiar to miners, although it was recognized much earlier that the occupation was not health-

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, M. M. Leighton, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

ful. With the decay of the Roman empire and Roman mining industry references to mines and miners disappear, and there are no contributions to the subject of miners' diseases during the entire medieval period. No definite information is available until Agricola and Paracelsus, in the 16th century, who placed the investigation of occupational diseases of miners on a firm basis. A growing literature in the 17th and 18th centuries indicated considerable interest in the subject although there were no important discoveries.

Accelerated development of pathologic anatomy, following the French Revolution, and the rapid advance of industry, especially in England, highlighted the problem of occupational diseases in miners and the subject was taken up vigorously in the 19th century. The history of such diseases at this period was indubitably linked with the mining of coal, which is considered in detail. From the 1830's on definite data is to be found on the prevalence of occupational diseases. The author emphasizes, however, that considerable caution is required in its interpretation and, in his chapter on Morbidity and Mortality, exercises this caution to present an extremely accurate picture.

The accomplishments of the 19th century were to clarify the origin and nature of various conditions prevalent among miners, to collect a definite body of knowledge, and to establish firmly upon a scientific basis the investigation of pathological and clinical aspects of such diseases. Following chapters on Pathology, and Therapy and Prophylaxis, the author traces the beginnings of social and protective legislation which, he reminds, had practically no connection with the contemporary medical study of diseases among miners. The coordination of medical research and social reform for improving the health of the miner was to be the accomplishment of the 20th century.

Rosen's careful consideration of so many aspects necessarily concerned in the history of miners' diseases and his critical interpretation result in a book of as much interest to geologists and sociologists as to members of the medical and public health professions.

E. M. W.

Colorimetric Determination of Traces of Metals. By E. B. SANDELL. Pp. xvi + 487; Figs. 73. Interscience Publishers, Inc. 215 Fourth Avenue. New York, 3, 1944. Price, $7.00.

This modern text on the analysis of chemical substances for the micro-constituents should prove a most useful addition to the literature of chemistry. Trace analysis, a branch of chemistry which has received its most rapid advancement in recent years, will doubtless become of greater

and greater importance as the significance of its findings becomes better realized.

The book is divided into a "General Part" and a "Special Part." The former, occupying roughly a fifth of the book, discusses first the methods and precautions necessary in trace analysis. Methods for the separation and isolation of traces of chemical substances are discussed in a general way in the second chapter. The most important determination procedures, colorimetry, spectrophotometry, fluorimetry, turbidimetry, and nephelometry form the subject matter of Chapter III. A chapter treating the important colorimetric reagents in considerable detail concludes the general part.

The special part, as is pointed out by the author in his preface, aims to present a limited number of methods which appears at the present time best suited for the trace analysis of the metals. Methods for forty-five metals and the rare earths are presented in detail. Separations as well as methods of determination are considered. The detailed directions for the procedures start with a convenient list of reagents and any necessary directions as to their preparation. A third section of each discussion gives details for various applications of the methods. Among these are to be found applications to biological and to mineralogical materials. Many references to the original literature enhance the value of the discussions.

The book manufacture of this work is excellent. The typography is simple and clear; formulae and figures are well set forth. The subject index appears to be most complete. This writer can find little to criticize in the book. It is true that little or no discussion is included of the upper limits of the effectiveness of various separations. This, however, may well be a criticism of the incomplete state of development of this branch of chemistry. It is to be hoped that this excellent book will encourage more detailed research in its field.

H. C. THOMAS

Geology For Everyman. By SIR ALBERT SEWARD. Pp. xi + 312; Figs. 10; Pls. 8. University Press, Cambridge; Macmillan Co., New York, 1944. Price, $3.25.

Some of the most profound and important contributions to geology to come out of England have been the products of men for whom geology began and long remained a diversion from other pursuits. James Hutton and William Smith would top this list. In more modern times the British Isles still claim many devotees among amateur naturalists. The author of this splendid little book took it upon himself to emphasize

the delight which geology affords the nature lover. His aim was "—— to present a case for the inclusion of geology as part of general culture." The book should do much to accomplish this purpose, for it is written in a lucid, interesting manner with a definite scientific bent. It is indeed unfortunate that Sir Albert Seward did not live to see his work published. The book culminated a long and active career in botany, geology, and paleobotany; part of his interesting life was spent as Professor of Botany in the University of Cambridge.

Unlike many popular accounts of geology, this book contains very few statements which would raise the eyebrows of professional geologists. In his description of the historical geology of the British Isles, Seward departs from long accepted procedure and begins with the Pleistocene and works back to Precambrian. This method has much logic and is worthy of the consideration of future writers of elementary geology texts.

RALPH E. DIGMAN.

BOOKS RECEIVED.

RALPH E. DIGMAN.

U. S. Geological Survey. Washington, 1943–1944.

Bull. 928–B. **Geology and Ore Deposits of the Shaffer Mining District, Presidio County, Texas.** CLYDE P. ROSS. Pp. 78; Figs. 5; Pls. 7. Price, 65 cents.

Bull. 930–D. **Spirit Leveling in Illinois, 1896–1942, Pt. 4, Northern Illinois.** Pp. 421; Figs. 68; Pls. 4. Price, 45 cents.

Bull. 933–B. **Geology of the Nutzotin Mountains, Alaska and Gold Deposits Near Nabesna.** F. H. MOFFIT AND R. G. WAYLAND. Pp. 96; Figs. 4; Pls. 11. Price, 65 cents.

Bull 936–Q. **The Coso Quicksilver District, Inyo County, California.** C. P. ROSS AND R. G. YATES. Pp. 21; Pls. 4. Price, 40 cents.

Bull. 940–D. **Vanadium-bearing Magnetite-ilmenite Deposits Near Lake Sanford, Essex County, New York.** J. R. BALSLEY, JR. Pp. 24; Figs. 5; Pls. 5. Price, 60 cents.

Bull. 940–E. **Occurrence of Manganese in Eastern Aroostook County, Maine.** W. S. WHITE. Pp. 36; Fig. 1; Pls. 5. Price, 25 cents.

Bull. 940–F. **Manganese Deposits of the Lyndhurst-Vesuvius District, Augusta and Rockbridge Counties, Virginia.** M. M. KNECHTEL. Pp. 35; Figs. 4; Pls. 6.

Bull. 941. **Geology of the Coastal Plain of Georgia.** C. W. COOKE. Pp. 121; Fig. 1; Pl. 1. Price, $1.25.

Prof. Pap. 199–A. **Mollusca from the Miocene and Lower Pliocene of Virginia and North Carolina. Part 1, Pelecypoda.** JULIA GARDNER, With a summary of the stratigraphy by W. C. MANSFIELD. Pp. 178; Figs. 4; Pls. 23. Price, 55 cents.

Prof. Pap. 201. **Geology and Ore Deposits of the Cottonwood-American Fork Area, Utah.** F. C. CALKINS AND B. S. BUTLER,

With sections on history and production by V. C. HEIKE. Pp. 152; Figs. 8; Pls. 51. Price, $1.75.

Prof. Pap. 203. **Stratigraphy and Fauna of the Louisiana Limestone of Missouri.** J. S. WILLIAMS. Pp. 133; Figs. 9; Pls. 9. Price, 50 cents.

W. S. P. 889–B. **Water-table Fluctuations in the Spokane Valley and Contiguous Area, Washington-Idaho.** A. M. PIPER AND G. A. LA ROCQUE, JR. Pp. 56; Figs. 4; Pls. 4. Price, 30 cents.

W. S. P. 923. **Surface Water Supply of the U. S., 1941. Part 3, Ohio River Basin.** G. L. PARKER AND OTHERS. Pp. 623; Pl. 1. Price, 75 cents.

W. S. P. 954. **Surface Water Supply of the U. S., 1942. Part 4, St. Lawrence River Basin.** G. L. PARKER AND OTHERS. Pp. 202; Pl. 1. Price, 30 cents.

W. S. P. 958. **Surface Water Supply of the U. S., 1942. Part 8, Western Gulf of Mexico Basins.** G. L. PARKER AND OTHERS. Pp. 285; Pl. 1.

W. S. P. 964. **Surface Water Supply of the U. S., 1942. Part 14, Pacific Slope Basins in Oregon and Lower Columbia River Basins.** G. L. PARKER AND OTHERS. Pp. 231; Pl. 1.

U. S. Bureau of Mines. Washington, 1944.

Bull. 454. **Fundamentals of Coal Sampling.** B. A. LANDRY. Pp. 127; Figs. 41. Price, 20 cents.

Bull. 456. **Coal-Mine Accidents in the U. S., 1941.** W. W. ADAMS AND L. E. GEYER. Pp. 131. Price, 20 cents.

Tech. Pap. 660. **Coke-Oven Accidents in the U. S., 1942.** W. W. ADAMS AND V. E. WRENN. Pp. 21; Figs. 3. Price, 10 cents.

Review of Petroleum Geology in 1943. F. M. VAN TUYL AND OTHERS. Pp. 127; Pls. 4. Quarterly of the Colorado School of Mines, Vol. 39, No. 2. Golden, 1944. Price, $1.00. *Here is another excellent Colorado School of Mines' Petroleum Reviews. Following the pattern of previous numbers, a review of the advance in petroleum geology during the past year is given, and production and reserve figures are presented. Several other interesting articles are included, Aerial Photographs, New and Improved Techniques, Noteworthy Discoveries, etc.*

Mineral Resources of South Carolina. S. TABER AND OTHERS. Pp. 13; Fig. 1. South Carolina State Planning Board, Bull. 3 (reprint). Columbia, 1944.

Reconnaissance of Pleistocene Deposits in North-central Kansas. C. W. HIBBARD AND OTHERS. Pp. 28; Figs. 2; Pls. 2. Kansas Geol. Surv., Bull. 52, Part 1. Lawrence, 1944.

Ground-water Conditions in the Neosho River Valley in the Vicinity of Parsons, Kansas. CHARLES C. WILLIAMS. Pp. 47; Figs. 9; Pls. 3. Kansas Geol. Surv., Bull. 52, Part 2. Lawrence, 1944.

Subsurface Structure and Oil Possibilities of Parts of Clay, Marion, and Wayne Counties. W. H. EASTON. Pp. 7; Figs. 2. Illinois Geol. Surv., Press Bull. Ser., No. 48. Urbana, 1944.

SOCIETY OF ECONOMIC GEOLOGISTS

HENRY A. BUEHLER.

1876–1944.

Those who were fortunate enough to know him mourn the death of Henry A. Buehler. He was a friend of the most dependable kind, a scientist of the best type, and a rarely devoted public servant. His religion was one of service to the state of Missouri, and he served it with outstanding devotion all the mature years of his life.

Born at Monroe, Wisconsin, he was trained as a chemist at the University of Wisconsin. On graduation he went to Rolla as chemist for the Missouri Bureau of Geology and Mines under Buckley, whom he later succeeded as State Geologist.

His geologic interests were wide. While most of his energy and time were occupied with the economic geologic resources of the state he was also deeply interested in its physiography, paleontology, stratigraphy, and in the applications of geophysics. He practiced the precept that geology is the application of all sciences to the study of the earth.

His work in the lead and zinc areas was of great help in promoting their development and the extension of mining activity. One of his strong interests was the geology of the sink-hole deposits of his state. The iron oxide, the sulphides, the coal, and the rare and valuable clays found in the sink-holes interested him exceedingly, both for their economic value and for their evidences as to paleo-physiography.

His unselfish devotion to the service of his state and the outstanding quality of his work won him the respect of geologists and mining men throughout the country. His lovable personal qualities won him the friendship of all those with whom he came in contact. Recognition came to him that pleased both him and his host of friends. The University of Missouri conferred an honorary doctorate upon him, and the American Institute of Mining and Metallurgical Engineers elected him as its president in 1935, and the Society of Economic Geologists as Councilor in 1944.

For many years he has been the beloved dean of American State geologists. Many will miss deeply his presence at our gatherings. We were all proud to call him "Chief."

WILLIAM O. HOTCHKISS.

ROY ERNST DICKERSON.

1877–1944.

Dr. Roy Ernst Dickerson, Chief of the Technical Section of the Petroleum Division, Foreign Economics Administration, died on February 24, 1944, as he was returning home from the annual meeting of the American Institute of Mining and Metallurgical Engineers.

Born in Monticello, Illinois, August 8, 1877, he graduated at twenty-three from the University of California and ten years later obtained the Master of Science degree. At California he continued his studies of the Eocene sediments and faunas under the direction of John C. Merriam, earning the doctorate in 1914. In 1904 he married Miss Delle Howard of Cloverdale, California, who survives him.

For eighteen years, despite a very successful career as teacher and administrator in the California high schools, he found time to school himself as a geologist, to assist in several University Field Camps, and to organize the geological collections of the California Academy of Sciences. For the latter service he was appointed Assistant Curator of Paleontology in 1914, Curator in 1917 and one year later, Honorary Curator. He entered his professional field in 1918 with studies of Pacific Coast areas but soon became Geological Superintendent for the Richmond Petroleum Company, a subsidiary of the Standard Oil Company of California and spent the period of 1919–1925 in the Philippines and the Netherlands East Indies. While there he also handled lands and lease matters with the governments involved.

Returning to this country, Dr. Dickerson became chief geologist of the foreign division of the Atlantic Refining Company, a position creditably held until 1942, when he accepted the position in the Foreign Economic Administration. As petroleum geologist, he was concerned with explorations in Bolivia, Peru, Ecuador, Colombia, Venezuela, Trinidad, Cuba, Haiti, and several central American countries.

He held membership in six leading geological and mining societies (including the Society of Economic Geologists) and was a member of Sigma Xi, California Academy of Science, Explorers Club and others. He held offices in the Pacific Division of the Paleontology Society of America. A frequent attendant at scientific meetings, he often read papers or contributed discussions of especial interest.

His published papers were concerned principally on the early Tertiary, the Orient, and later on the Cretaceous of Honduras and the Jurassic of Cuba. Dickerson's contributions to the knowledge of the Eocene faunas and the stratigraphy of California were most important; this applies notably to the monographs of the Martinez and the Tejon, which furnish basic material on the stratigraphy and faunas, thus stimulating further study by others and resulted in the present subdivision of the California Eocene.

By the large group who knew him personally Dickerson will be remembered not only for his conspicuous scientific achievements but for his open friendliness, many kindnesses and his readiness to assist others in solving their personal or scientific problems.

E. L. PACKARD.

SCIENTIFIC NOTES AND NEWS

The A.I.M.E., in accordance with a request of the President of the PAN AMERICAN INSTITUTE OF MINING ENGINEERING AND GEOLOGY, headquarters in Santiago, Chile, appointed a "steering committee" to organize a national section in the United States. At a meeting of this committee, held in New York on April 17, it was decided that it is most desirable that a national section of PAIMEG be formed without delay and a National Directorate was elected. Members of any mineral industries society in the United States and Canada are eligible to join the National Section. Individuals paying 1944 dues, amounting to five dollars (no initiation fee) before December 31, 1944, will be recorded as Charter Members. Membership must be based on willingness to aid in fostering good will and better understanding among mineral industries engineers and technologists in the Western Hemisphere. Anyone interested in joining as a charter member is requested to forward dues to Edward Steidle, Chairman, National Directorate, PAIMEG, State College, Pennsylvania, or to Arthur T. Ward, Secretary-Treasurer, National Directorate, PAIMEG, 50 Church St., New York City. Minutes of the organization meeting will be forwarded to all members.

P. F. KERR, professor of mineralogy, has been named executive officer of the department of geology at Columbia University.

G. B. LANGFORD, formerly of the University of Toronto, is now Director of Planning and Development for the Ontario government.

J. M. KELLY, state geologist of New Mexico, has been named director of the State Bureau of Mines.

E. L. DEGOLYER is studying the petroleum potentialities in Brazil at the invitation of the Brazilian government.

W. H. EMMONS, head of the department of geology at the University of Minnesota, was one of four members of the faculty who retire June 30, honored at an informal reception on May 28.

R. S. POOR, head of the department of geology at Brmingham-Southern College, has been appointed dean of graduate studies and director of the Research Council of the Alabama Polytechnic Institute.

ALONZO QUINN, associate professor of geology at Brown University, has been elected vice-chairman of the Council on Mineral Industries of New York and the New England states.